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Rajender Kumar Yadav
Parbodh Chander Sharma *Editors*

Research Developments in Saline Agriculture

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Foreword

Today humanity faces a double whammy of food insecurity and population growth. The world's food supply is already threatened by climate change. On the one hand, in the past 20 or so years, there have been abrupt slowdowns, plateaus, or declines in the rate of production of major crops like rice, wheat, and maize in major cereal-producing regions around the world. A study by a team of scientists at the University of Nebraska-Lincoln points out that nearly 31% of total global rice, wheat, and maize production has seen plateaus or sharp decreases in yield gain. Climate change and degradation of land and other natural resources are singled out as some of the main causes.

On the other hand, one-third of the total amount of food produced globally is lost or wasted every year. A recent analysis by the Boston Consulting Group estimates that it is 1.6 billion tonnes of food worth about 1.2 trillion USD, which is projected to increase if not addressed. That is an unsettling excess at a time when some 870 million people are undernourished worldwide.

As the global population is forecast to hit 9.7 billion by 2050, these problems provide some context for the scale of the task ahead. History has, however, a precedent when science helped to transform global agriculture and save millions of people from hunger and poverty in what came to be known as the green revolution. Once again, we need to enlist the power of science in tackling the global challenges.

On the food production front, saline agriculture holds great promise as new arable lands and freshwater resources are in short supply. It is a means to adapt to salinization of soil and water resources, which is undermining agricultural production. Salinization is causing huge economic losses today in many countries where agriculture is a major contributor to gross domestic product (GDP).

Although it is partly a result of natural processes in certain environments, human activities such as inappropriate irrigation practices, among many others, are the major cause of salinization globally.

In their study, Qadir et al. note that every day for over 20 years, an average of 2000 hectares of irrigated land in arid and semiarid areas in 75 countries have been degraded by salt. They point out that about 62 million hectares, or 20% of the world's irrigated lands, have been affected by salinity to varying degrees, up from 45 million hectares in the early 1990s. They put the global inflation-adjusted annual cost of salt-induced land degradation in some 310 million ha of irrigated areas at 27.3 billion USD because of lost crop production only.

In view of these worrying figures, it is more important than ever before to enhance productivity and utility of lands and water resources degraded by salinity and other factors to meet future food demand.

These resources should be viewed as assets rather than liabilities. Every type of land and water suitable for agricultural production should be used as the UN Food and Agriculture Organization projects a need to produce 70% more food by 2050, including a 50% rise in annual cereal production to about 3 billion tonnes.

It is necessary to tap into the huge potential of saline water resources, as well as other types of non-freshwater, in addition to improving water efficiency and productivity. The competing demands of the agricultural, energy, industrial, and domestic sectors will only intensify due to urbanization and population growth.

Scientists have already done a great deal of work to study ways to improve agricultural production and ecosystem resilience on salt-affected lands and in other degraded environments through cultivation of non-conventional plants that are naturally resistant to salinity, heat, and drought, as well as the use of innovative technologies. There has also been considerable research on cultivation and the use of halophytes for different purposes, including food.

Thanks to these research efforts, there are now many solutions available to mitigate and adapt to salinization ranging from agroforestry to integrated agri-aquaculture systems.

This compilation presents a synthesis of many studies and approaches in various disciplines to saline agriculture specifically and salinity management generally.

All contributors are recognized experts in their relevant fields and have shared their knowledge and experience to enrich this volume. I would like to sincerely appreciate their contributions and the efforts of the editors who have made sure this publication is of high standard and quality.

I hope this publication will serve as an important resource for scientists, policymakers, environmentalists, and everyone who cares about the environment, salinity, and food security.

International Center for Biosaline Agriculture (ICBA) Ismahane Elouafi
Dubai, UAE

Preface

Soils, made up of inorganic and organic compounds, liquid, gases, living organisms, and soluble salts, are a natural surface feature of the landscape. Salts are present usually in small amounts in all waters, soils, and rocks. Under certain conditions, these salts accumulate by a process called "salinization." Thus, soil salinization is the accumulation of water-soluble salts within soil layers above a certain level that adversely affects crop production, environmental health, and economic welfare. Soil salinity is generally described and characterized in terms of the concentration and composition of the soluble salts. Even though soluble salts are inherent in all soils, there are many processes (such as weathering of soil minerals, salt added through rains, agronomic practices such as fertilizer and pesticide application and irrigation with poor-quality waters, saline groundwater intrusion with water table fluctuations, dumping of industrial and municipal wastes, etc.) that contribute to the buildup of salts in soil profile. In coastal areas, due to increase in sea level, seawater intrusion onto land deposits a large amount of salts in soil. Salt is also carried through wind and deposited on vegetation and soil in these areas. Thus, all soil types with diverse morphological, physical, chemical, and biological properties may be affected by salinization.

Being one of the oldest environmental problems, salinization has been considered as "one of the seven main paths to desertification" and "a major process of land degradation." Soil salinity is a major constraint in crop production, affecting more than 100 countries, worldwide. Globally, more than 800 million hectares of land, accounting for nearly 6% of the world's total land area and approximately 20% of the total agricultural land, is affected by salinity. Depending upon the nature of salts, these soils are classified as saline, saline-sodic, and sodic. The extent of salt-affected soils is highest in Asia-Pacific region countries like China, Egypt, India, Iran, Pakistan, Thailand, and Australia. Other major countries outside this region are Argentina, Russia, and the USA. Generally, salt-affected soils are predominant in arid and semiarid regions.

Further, the availability of good-quality water is scarce, and the use of saline groundwater in agriculture is inevitable. In most of the arid and semiarid regions, especially under deserts, the groundwater aquifers are saline or sodic, and these waters are being utilized since time immemorial for irrigation. Now, the data available indicate that saline groundwater is used for irrigation in at least 50 countries throughout the world. In coastal areas, the salinity problems are more complex, and in the scenario of climate change and sea-level rise, these problems will aggravate and more and more areas will turn saline due to intrusion of seawater in good-quality aquifers.

Technological knowledge generated till date has helped in taming the soil salinity problem and restoring their full potential in large tracts of land in different countries. However, new challenges are set to be faced either due to changing climate or land-use anomalies, leading to exponential increase in the area under salinity. With new challenges cropping up, soil salinity-related stresses can be more pronounced and more damaging to crop production in the coming years. Identifying gaps in our knowledge, therefore, is of utmost importance to understand the threats and convert them to opportunity to enhance crop and land productivity.

The Central Soil Salinity Research Institute (CSSRI), an Indian Council of Agricultural Research (ICAR) Institute at Karnal, Haryana, India, during its journey approaching 50 years, since its inception in 1969, has made impressive contributions in terms of development of technologies for reclamation and management of salt-affected soils and waters. Besides US Soil Salinity Laboratory, CSSRI is the only institution in the world completely dedicated to the development of technologies for salty land and water management for crop production. It has been in the forefront, for the last couple of decades, in developing technologies for holistic management of salty soils and waters and extending them to millions of farmers through its robust extension mechanism. In the context of climate change, the institute has guarded itself to develop mechanisms for mitigation and adaptation of environment-friendly smart agricultural practices to handle salt and climate stress-related problems. On its 50th anniversary year 2019, CSSRI in collaboration with the Indian Society of Soil Salinity and Water Quality brought together the international scientific community devoted to salinity research through its “Golden Jubilee International Salinity Conference on Resilient Agriculture in Saline Environments under Changing Climate: Challenges and Opportunities” from 7 to 10 February, 2019. The conference aimed to lay a strong foundation for rejuvenated research efforts and to build international collaborations to combat land and water salinization and strengthen world food security in backdrop of climate change. Besides other activities, it was planned to bring out a book entitled *Research Developments in Saline Agriculture*. The contents of the book are classified into five major themes: introduction, history, and perspectives; drivers, stressors, and indicators; salinization mechanisms and impacts; management opportunities and strategies; and impact assessment, policies, and socioeconomic issues. Many renowned research workers engaged in diversified fields of salinity have contributed 31 chapters in the fields of their specialization. The book covers historic perspectives of salinity; modern technologies of salinity mapping including optical and radar remote sensing and synergy between Sentinel-MSI and Landsat-OLI; diagnosis and prognosis of salty soils and waters; drivers, stressors, and indicators of salinity including salinity tolerance indicators, salt-plant-microbe interactions, and their ecological role; current understanding of mangrove forests; salinization processes, mechanisms, and impacts including engineered polymeric and nano-materials for taming salty soils and waters; potential pollutants in soil and irrigation waters; management opportunities and strategies to be adopted in changed environment; developing vegetable-, forest-, and fruit tree-based agroforestry and integrated farming systems and engineering and biological approaches for reclamation of waterlogged saline soils; and impact assessment, policies, and socioeconomic issues addressing gender and other socioeconomic dimensions.

This publication attempts to bring forward various issues and challenges being faced by the scientific ferternity to deal with saline agriculture especially in harmonizing synergy from salt-affected soils and utilization of poor-quality waters for irrigation purposes. Possibilities of several alternatives to utilize sodic, saline, and other poor-quality waters have been explored. We need to develop multi-stress-tolerant crops using modern tools of molecular biology and genetic engineering. Introgression of salt- and drought-tolerant genes/QTLs employing modern biotechnological approaches and marker-assisted breeding in high-yielding mega varieties of different food crops would help mitigate the adverse effects of climate change on food security. Above all, we need policy support to implement rehabilitation programs. All these aspects have been addressed in this publication.

We hope that the publication would be of immense use to researchers in planning their future line of research, environmentalists to understand the biodiversity of saline habitats including mangroves and mechanism of unique saline ecosystems, farmers and other stakeholders to find out the solutions of their problems, and students for awareness regarding vital issues of environment and for policy-makers to take rational decisions to implement the policies in this vital area of land and water degradation.

The editors thank all the contributors to this volume for their excellent efforts and timely submission of chapters and hope that this book will open new vistas in the field of saline agriculture. We are also thankful to Dr. Ismahane Elouafi, Director General, International Center for Biosaline Agriculture (ICBA), Dubai, UAE, who readily agreed to write the foreword for this publication.

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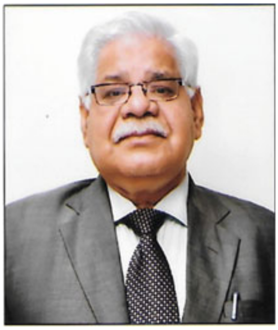
About the Editors



Dr. Jagdish Chander Dagar Former Assistant Director General and Emeritus Scientist in ICAR, has been well recognized both nationally and internationally for conducting, guiding and managing research in the fields of ecology, agricultural sciences and agroforestry which is evident from his more than 280 research papers published in peer-reviewed journals, book chapters and proceedings of conferences/symposia. He has also authored/edited 17 books and published 9 research bulletins. His research interest has been in the areas of biosaline agriculture, agroforestry, management of natural resources, rehabilitation of degraded lands, biodrainage, ethnobotany, plant ecology, climate change, sustainable agriculture, and policy issues. Recognizing the research contributions, he was conferred with several awards and honors: Sajjad Memorial Gold Medal, Hari Om Ashram Trust Award of ICAR, Swami Pranavananda Saraswati National Award of UGC, CSSRI Excellence Award on Soil Salinity and Water Management, and Dr. KG Tejwani Award for Excellence in Agroforestry Research and Development. Further, he is Fellow of the National Academy of Agricultural Sciences and several other professional societies. He has also been consulting several national and international agencies such as Food and Agriculture Organization (FAO) of UN, International Maize and Wheat Improvement Center (CIMMYT), and Haryana Forest Department. Dr. Dagar is Chief Editor of *Journal Soil Salinity and Water Quality* and also active in social services.

Dr. Rajender Kumar Yadav is presently working as Principal Scientist and Head of the Division of Soil and Crop Management, ICAR-Central Soil Salinity Research Institute, Karnal, India. He is a disciplined Agronomist and contributed 53 research papers published in high-impact peer-reviewed journals, 46 papers in the proceedings of national and international conferences/symposia, and chapters in books and has written 10 books/bulletins. Dr. Yadav has been awarded National Groundwater Augmentation Award (Ministry of Water Resources, Govt. of India), Ganesh Shankar Vidyarthi Puraskar (ICAR), and Commonwealth Scientific and Industrial Research Organization (CSIRO) Australia Fellowship. He is Fellow of the Indian Society of Agronomy and Indian Society of Soil Salinity and Water Quality. He is handling several important national and international projects. He has visited several countries in various capacities. He is General Secretary of the Indian Society of Soil Salinity and Water Quality and also active member of several scientific professional societies.

Dr. Parbodh Chander Sharma presently working as Director, Central Soil Salinity Research Institute, Karnal (India), was earlier Program Leader for improvement of rice, wheat, Indian mustard, and chickpea for salt tolerance and high yield as Head, Division of Crop Improvement. He has made significant contributions in understanding the physiological mechanisms under salinity stress in different crops and was involved in developing salt-tolerant high-yielding genotypes of Indian mustard (CS 56, CS 58, and CS 60), rice (CSR 46), and wheat (KRL 283), besides improving three popular mega varieties of rice (Pusa 44, PR 114, and Sarjoo 52) for salinity tolerance by introgression of *SALTOL* QTL following molecular marker-assisted backcross breeding. Further, significant contribution is in developing crop and resource management practices for sustainable future cereal-based systems following conservation agriculture. He has been awarded fellowships of three professional societies. He is also the President of the Indian Society of Soil Salinity and Water Quality since 2016. He has more than 100 research publications in peer-reviewed research journals.

Part I

Introduction, History and Perspectives

1

Historical Perspectives and Dynamics of Nature, Extent, Classification and Management of Salt-affected Soils and Waters

J. C. Dagar, R. K. Yadav, Awtar Singh, and N. T. Singh

Abstract

Soluble salts are a natural feature of the landscape, being present usually in small amounts in all soils, waters and rocks. It is only their accumulation beyond a certain proportion that creates a salt land. Soil salinization is an *in situ* form of soil degradation that arises due to the buildup of soluble salts to deleterious levels at or near the soil surface. Being one of the oldest environmental problems, salinization has been considered as 'one of the seven main paths to desertification' and a major process of land degradation. Salt-affected soils occur in about 100 countries under different environmental conditions and have diverse morphological, physical, chemical, physico-chemical and biological properties, but one common feature, the dominating influence of electrolytes on the soil-forming processes, joins them into one family. There are many classification systems for salt-affected soils, while a large number of systems exist in individual countries, particularly in those where salt-affected soils are common. Saline soils develop mainly under the influence of sodium chloride and sulphate and closely associated with deserts and semiarid regions and seldom occur in subhumid and humid regions. Alkali soils, formed under the influence of sodium ions capable of alkaline hydrolysis, occur mainly in semiarid, subhumid and humid regions, but they can also be found under practically any environmental conditions.

Beneath many of the world's deserts are reserves of saline water, and the information for saline water use for irrigation on global perspective is reported from about 50 countries. FAO has also published the standard water quality criteria for saline irrigation. To meet the requirement of good-quality water, for

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drinking and other uses of ever-increasing population, will make the use of poor-quality waters inevitable. The concerted research efforts have shown that the degraded salt-affected lands and poor-quality waters can be put to sustainable productive use by adopting suitable strategies and remunerative alternate uses through agroforestry adopting appropriate planting and management techniques. In the present chapter, a brief historical perspective and dynamics of nature, extent, classification and management aspects of salty soils and waters have been dealt in brief.

Keywords

Salt-affected soils · Saline soils · Alkali/sodic soils · Secondary salinization · Historical perspectives · Reclamation measures · Poor-quality waters

1.1 Introduction

Salts are not alien to the land. Soluble salts are a natural feature of the landscape, being present usually in small amounts in all soils, waters and rocks. It is only their accumulation beyond a certain proportion that creates a salt land. Under certain conditions, these salts accumulate through a process called salinization. Soil salinization is an *in situ* form of soil degradation that arises due to the buildup of soluble salts to deleterious levels at or near the soil surface (Schofield et al. 2001). Being one of the oldest environmental problems, salinization has been considered as 'one of the seven main paths to desertification' (Kassas 1987) and a major process of land degradation (Thomas and Middleton 1993). Salt-affected soils occur under different environmental conditions and have diverse morphological, physical, chemical, physico-chemical and biological properties, but one common feature, the dominating influence of electrolytes on the soil-forming processes, joins them into one family (Szabolcs 1979). A certain concentration of electrolytes determines not only the morphology of the soil profile, but also other properties which result, as a rule, in low fertility and limited agricultural value on land affected by salinity (Szabolcs 1989).

Beneath many of the world's deserts are reserves of saline water. The major occurrences of saline waters are in the Thar Desert of the Indian subcontinent, the Arab Desert of the Middle East countries, the Sahara Desert in North Africa, the Kalahari Desert in Southern Africa, the Atacama Desert in South America, the California Desert in North America and the West Australian Desert. The information for saline water use on the global prospective is reported from about 50 countries, which are using saline water for irrigation in one or other forms. These countries are virtually from the semiarid and arid regions, except some developed nations, which make use of the wastewater for irrigation. Rhoades et al. (1992) reported the use of saline water in irrigation in many countries. With increasing demands of agricultural produces and other necessities for ever-increasing population and limited availability of good-quality water, saline water irrigation is now considered as an imperative necessity for the sustainable agricultural development, which includes the use of saline groundwater, saline drainage water and sewage for irrigation.

In the present chapter, an attempt has been made to compile information on historical perspectives of nature, classification and management issues of salt-affected soils and also judicious use of saline water both groundwater and seawater by applying modern technologies for agricultural production.

1.2 Natural Incidences of Salinity (Historical Perspectives)

Salinity has been existing with mankind since the beginning of agriculture. Though its existence has been always ecologically important in arid and semiarid regions of the world, the adverse effects of the problem were realized only when it staked the food and nutritional security of the population. Many authors have described the consequences of the extension of salinity, which has developed in the irrigated areas of the world due to primitive or incorrect technologies (Thorne and Peterson 1954; Jacobsen and Adams 1958; Hobbs and Russell 1967; Talsma and Philip 1971; Szabolcs 1986, 1989). It is well known that in ancient Mesopotamia, an area of fertile soils between the rivers Tigris and Euphrates, quantities of grain and other crops sufficient to feed large population were produced for a long time. In modern times, this area has been known only as a bare desert. It is also well known that in ancient China, in the Indus Valley (Dregne 1967) and in South America, vast territories were turned into deserts because of salinity problems resulting from faulty irrigation by ancient societies. The problem of secondary salinization runs through the whole history of mankind (Balba 1976). Jacobsen and Adams (1958), while explaining progressive changes in soil salinity in ancient Mesopotamian agriculture, stated that as to salinity itself, three major occurrences were established from ancient records: (i) The earliest of these, and the most serious one, affected southern Iraq from 2400 BC to at least 1700 BC; (ii) a milder phase attested in documents from central Iraq written between 100 and 900 BC; and (iii), lastly, there was archaeological evidence that the Nahrwan area east of Baghdad became salty only after 1200 AD. Several parallel lines of evidences allow the ensuing salinization to be followed quantitatively. For example, crop choice could be influenced by many factors, but the onset of salinization strongly favoured the adoption of crops which were more salt-tolerant. Counts of grain impressions in excavated pottery from sites in southern Iraq of about 3500 BC, made by H. Helbaek (cited by Jacobsen and Adams 1958), suggest that at that time the proportions of wheat and barley were nearly equal. A little more than 1000 years later, in the time of Entemenak at Girsu, the less salt-tolerant wheat accounted for only one-sixth of the crop. By about 2000 BC, the cultivation of wheat accounted for less than 2% of the crop in the same area, and by 1700 BC, the cultivation of wheat had been abandoned completely in the southern part of the alluvium. Further, concurrent with the shift to barley cultivation was a serious decline in fertility which for the most part could be attributed to salinization. At about 2400 BC in Girsu, the yield was respectable and comparable to the Canada and USA standards, but the same declined by 43% by 1700 BC and further deteriorated to one-third of the initial. The southern part of the alluvial plain appears never to have recovered fully from the disastrous general decline in fertility which accompanied the salinization process.

Tracing the history of salinity in the Indian subcontinent, Singh (1998a) reported that in ancient India, between 2500 BC and 600 AD, soils were known as *urvara* (fertile) and *anurvara* (desert); however, salinity was recognized as a potential threat to agriculture only during the middle of the nineteenth century. Now, there is an increased awareness about secondary salinization in irrigated command areas. In north and north-western India, salt-affected soils were known as *kallar*, *usar* or *reh* even before the arrival of the British, but the earliest recorded evidence of the presence of *usar* and indigenous methods of its reclamation in the united provinces of Agra and Oudh finds mention in the 1850 tour diary of Mr. Sleeman (Moreland 1901). He mentioned that farmers used to irrigate, manure, cross plough and flood *usar* fields for two to three consecutive seasons for reclamation; nevertheless, the soil was liable to become *usar* if neglected or left fallow for a few years. Sleeman's diary also suggested that reclamation of salt-affected soils using different methods was practised in the united provinces much before any scientific research had been conducted. The Director of Land Records and Agriculture correspondence of 1888 informed that about 12.72 million ha of area was affected by *usar* in north-western provinces and Oudh. Later, Tiwari et al. (1989) also reported similar extent of alkali lands in Uttar Pradesh. Leather (1897) further gave account of the vast extent, poor cultivation conditions and economic loss due to *usar* or *reh* land problem in plains of northern India. His account also suggested serious concerns of the government of North-western Province and Oudh for understanding and managing the problem. The problem was not restricted only to united provinces of Agra and Oudh and North-western Province, but the Indus plains of Punjab also suffered from soil salinity before introduction of any large-scale canal irrigation. Dr. Jameson, superintendent of the Botanical Gardens, during his visit of Punjab soon after annexation of the 'Sikh state' by the British in 1849, recorded that large area in Kapurthala (~77 km^2) lied barren due to want of water and soil salinity (Jameson 1852). The extent of the problem in Punjab can be understood by a communication in 1865, of an X-En of Punjab Irrigation Department, mentioning that 'whole of the country in Punjab lying west of Jamuna is impregnated with *reh* i.e. salts in soil and water in the proportions from traces to absolutely injurious to all vegetation'. Whitecombe (1971) reported development of variable-size patches of the *reh* efflorescence that increased westwards in the Barh, from Lahore to Multan and Shahnoor and from either of the places to the Derajat and foot of the Soolimani mountain.

The widespread problem of salt-affected lands also existed in Sind part of the Indus plain. It is evident from the government of India's call of 1906 asking experienced local irrigation and revenue officers for reports on the problem of *kallar* or *alkali* in Sind. The commissioner of Sind reported that extent and gravity of the problem could not be judged due to non-availability of any statistics and materials even for a rough estimate of any degree of reliability. As per reports of Henderson (1914) the saline area occurred from isolated patches to continuous many miles barren tract in Sind. He further suggested that the gravity of the problem cannot be measured only by ‘the domination in the cultivated area and the injury to the crops in localities where attempts are being made to control it but only the permanent exclusion from cultivation of large areas of otherwise valuable lands’.

1.2.1 Secondary Salinization Due to Irrigation

The expansion of irrigation not only resulted in more areas being irrigated but also affected the properties of the soils. Although the irrigation dates back to prehistoric times, its rapid development only started about in the beginning of the nineteenth century. It is clear from the fact that the global area of irrigated land grew from 8 million ha in 1800 to 48 million only in 1900 and was more than doubled by the next 75 years (Szabolcs 1989) and ultimately reached 310 million ha, out of which 117 million ha (38%) is irrigated with groundwater (FAO 2012). The main reservoir of saline water in arid and semiarid regions is the groundwater. The soluble salts accumulated in the groundwater, as a result of the geochemical processes, can cause salinity problems when this groundwater is used for irrigation. As long as groundwater table is deep and the moisture cannot come up through capillary flow to the rootzone soil profile, even saline groundwaters do not induce immediate salinization. As the effect of irrigation, the groundwater table may rise so high that it can reach the surface layers and cause salinization even when good-quality water is used for irrigation.

The natural or artificial drainage of irrigated land, or land to be irrigated, is also a major factor in the processes of secondary salinization. The irrigation was practised for thousands of years in the Nile Valley under the dry climate without any secondary salinization, but because of the introduction of perennial irrigation during the nineteenth century in Egypt, due to the change in salt and water regime, the Nile Delta became salinized, and an artificial drainage system became necessary to get rid of excess salts (El-Gabaly 1972). Thus, with the exception of places with good natural drainage, which is rather rare, in arid and semiarid regions, the lack of artificial drainage leads to secondary salinization, and as many as half of the existing irrigation systems of the world are more or less influenced by secondary salinization, alkalization and waterlogging (Szabolcs 1989).

Singh (1998a) also reported the development of secondary salinization due to irrigation in the Indian subcontinent. According to him the first official notice of land degradation due to the introduction of canal irrigation was lodged in 1855 by a farmer of ‘Moonak’ village in command of western Yamuna canal since its construction by Feroze Shah Tuglaq in the fourteenth century and remodelled by the British in 1839. The then British government, who planned a number of large irrigation projects in the country, took urgent action on understanding the causes and possible remedies to remove such fears of farmers. This is evident from probably the first selected correspondence records of the government, published in 1864, relating to the deterioration of lands in the command of western Yamuna canal leading to the development of soil salinity due to canal irrigation. The correspondence mainly dealt with the effects of canal on soil saturation but also described its role in alkali soil formation (Moreland 1901). Likewise, secondary soil salinization due to canal irrigation was also noticed in the peninsular India. Mann and Tamhane (1910) reported the appearance of barren, salt-encrusted spots, within 5 years, in some of the best and deepest soils in the command of Nira Valley irrigation canal opened first in 1884 to introduce large-scale irrigation in deep black soils. Development of salinization caused anxiety among farmers and the irrigation authorities. Based on analysis of soil samples, Dr. Leather (1893) reported that the salt lands were increasing rapidly, but the problem did not receive proper attention during the initial years. The matter ultimately got the needed attention in 1903 when a committee composed of Messrs Vishveshvaraya, PR Mehta and JB Knight was appointed to consider the issue. According to Mann and Tamhane (1910), it was the 1905 report of the above committee that received the most careful consideration of the situation up to that time. The committee recommendations issued as Resolution No. 8968 of the Revenue Department suggested the following (Singh 1998b):

1. Opening *nadies* (drainage) in the neighbourhood of low-lying lands affected by waterlogging and salt efflorescence
2. Measurement of affected survey numbers and their portions with remarks about their condition
3. Request to the agricultural department to observe the lands requiring improvement by the farmers and advise them in reclamation work

The government approved these recommendations, and the follow-up work was entrusted to the survey and agricultural departments.

1.3 Classification, Distribution and Characteristics of Salt-affected Soils

1.3.1 Classification

There are many classification systems for salt-affected soils. Some of these are incorporated into the generally accepted world soil classification systems, such as soil taxonomy, the classification system of the former USSR, the soil classification system of the FAO/UNESCO Soil Map of the World, Soil Map of Europe and many others. A large number of systems exist in individual countries, particularly in those where salt-affected soils are common; and there are local names and terms for different kinds of salt-affected soils in such countries, and it becomes difficult to find out correlation, if any, between them. Szabolcs (1989) has summarized the tentative correlation between the most widely used classification systems of these soils. At least five groups of salt-affected soils are influenced by different chemical types of electrolytes (Table 1.1). Saline soils developing mainly under the influence of sodium chloride and sulphate are closely associated with deserts and semiarid regions and seldom occur in subhumid and humid regions. These are the most widespread types of soils on the continents and, with the exception of Europe, are dominant within soil family. Alkali soils formed under the influence of sodium ions

Table 1.1 Grouping of salt-affected soils

Electrolytes causing salinity and/or alkalinity	Types of salt-affected soils	Environment	Main adverse effect on production	Method for reclamation
Sodium chloride and sulphate (nitrate in extreme cases)	Saline soils	Arid, semiarid	High osmotic pressure of soil solution (toxic effect)	Removal of excess salts through leaching
Sodium ions capable of alkaline hydrolysis	Alkali soils	Semiarid, subhumid, humid	Alkali pH, effect on water and soil physical properties	Lowering or neutralizing the high pH by chemical amendments
Magnesium ions	Magnesium soils	Semiarid, subhumid	Toxic effect, high osmotic pressure	Chemical amendments, leaching
Calcium ions (mainly $CaSO_4$)	Gypsiferous soils	Semiarid, arid	Acid pH, toxic effect	Alkaline amendments
Ferric and aluminium ions (mainly sulphates)	Acid sulphate soils	Seashores, lagoons with heavy sulphur-containing sediments	Strong acidic pH, toxic effects	Liming

Source: Szabolcs (1989)

capable of alkaline hydrolysis occur mainly in semiarid, subhumid and humid regions, but they can also be found under practically any environmental conditions, from the polar circle to the equator including at different altitudes from sea level to high mountains. Szabolcs (1989) has also recognized magnesium, gypsiferous and acid sulphate soils as important salt-affected soils.

Attempts were made to classify the soils on the basis of total soluble salts measured in terms of electrical conductivity of the soil saturation paste extract (ECe) or various dilutions (soil/water 1:2 or 1:5), exchangeable sodium percentage (ESP) or sodium adsorption ratio (SAR) and pH of the saturation paste (pHs) or other dilutions. The US Salinity Laboratory Staff in 1954 (USSL 1954) originally proposed the three categories of salt-affected soils on the basis of these parameters i.e. saline, saline-alkali and alkali soils. The definitions in respect of these three categories were slightly modified later by Soil Science Society of America (SSSA 1987). It was described that owing to excess salts (ECe 4 dS m^{-1} or 2 dS m^{-1} later on) and absence of significant amount of sodium (ESP 15), saline soils are generally flocculated, and as a consequence their conductivity is equal to or even greater than their nonsaline counterparts. A saline-alkali soil (ECe 4 dS m^{-1} or more; ESP 15 or more) was described similar to that of saline soils as long as sufficient salts are present, whereas upon leaching, these soils become alkaline (pH 8.5) leading to dispersion, and their permeability reduces to levels those affecting crop growth. The term ‘alkali’ was discarded later on to be replaced with ‘sodic’, and these soils contain sufficient exchangeable sodium (ESP 15) to affect the physical behaviour of soils and interfere with growth of the most of the crops.

Table 1.2 Classification of salt-affected soils under two systems

Soil group	Soil map of world (FAO/ UNESCO Project)	Soil classification (Soil Survey Staff 1975)
Saline soils	Solonchak	Salorthids
Alkali soils		
Without structural B horizon	Orthic solonchak	Salorthidic-calcuiustolls
	Mollic solonetz	Salorthidic-haplustolls
	Takyric solonchak	Halaquepts
	Gleyic solonchak	
With structural B horizon	Solonetz	Nadurargids, Natrargids, Natriboralfs, Natrudalfs, Natrustalfs, Natrixeralfs
	Orthic solonetz	Natralbolls, Natriborolls, Natrustolls
	Mollic solonetz	Natrixerolls, Nartaquolls
	Gleyic solonetz	Natraqualfs
	Solodic planosols	Argiabolls

Source: Sharma (1998)

The Indian classification of salt-affected soils is also based on the above criteria, but in place of three categories of salt-affected soils (saline, sodic and saline-sodic), these soils were classified into two groups based on the nature of plant responses to the presence of salts and the management practices desired for their reclamation. Abrol and Bhumbla (1978) concluded that ‘the so-called saline-sodic soils’ are in fact of rare occurrence, and only two categories ‘saline’ and ‘sodic’ were recognized.

Soil taxonomy (Soil Survey Staff 1975) and the World Soil Map Legend (FAO-UNESCO 1974) are the two internationally accepted systems of classifying the soils (Table 1.2). A feature common to both is the use of defined diagnostic horizons in different classes.

The existence of salt-affected soils in India, called *usar* (Raychaudhuri and Govindarajan 1970), has been reported since ancient times (2500 BC). Under the genetic system of soil classification, these soils were classified as *solonchak* or *solonetz* (Sharma 1998). The soil taxonomy has six categories which are grouped as higher categories, namely, order, suborder and great group, and another one is lower categories, namely, subgroup, family and series. Twelve orders have been recognized. Each order is distinguished due to strictly defined diagnostic horizons. In salt-affected soils of India, the most common epipedon (surface diagnostic horizons) is ochric, and the subsurface horizons are argillic, natric, cambic, calcic, gypsic and salic (Table 1.3) as described by Sharma (1998).

According to the soil taxonomy, the important and extensively occurring salt-affected soils of India are classified as:

Natraqualfs: These have a natric subsurface horizon and a perched water table, existing in canal command areas of the Indo-Gangetic plains.

Natrustalfs: These have a natric subsurface horizon and occurred in areas with rainfall <550 mm.

Natrargids: These exist in western parts of the country under arid climate.

Table 1.3 Characteristics of surface and subsurface horizons commonly existed in salt-affected soils

Sl. no.	Name of surface and subsurface horizon	Characteristics
1.	Ochric epipedon	This horizon is light in colour and have organic matter <1%. The horizon is hard or very hard when dry and does not qualify for any other horizon
2.	Argillic horizon	This is an illuvial horizon where substances leached and transported from an overlying eluvial horizon have been deposited over many years. This horizon must have more total and finer clay than the overlying horizon
3.	Natric horizon	It is an argillic horizon with either prismatic or columnar structure or with ESP >15 and has more exchangeable sodium plus magnesium than exchangeable calcium
4.	Cambic horizon	This is a horizon showing alterations in colours and textures in the neighbouring horizons, brought about by operative soil processes. This alteration is not definitive to qualify for any other diagnostic horizons
5.	Calcic horizon	This is a horizon of accumulation of more than 15% calcium carbonate
6.	Gypsic horizon	A horizon with enrichment of secondary sulphates
7.	Salic horizon	It contains secondary enrichment of water-soluble salts. The salt should be at least 2% in the horizon, and the product of its thickness (cm) and salt (% by weight) is ≥ 60

Some soils are also classified under Calciorthids, Camborthids and Salorthids (highly saline soils, mostly in the coastal regions). The suborders Psamments, Fluvents and Orthents may have salt-affected soils. Great groups Halaquepts and Ustochrepts have salt-affected soils, while the other great groups, Chromusterts and Pallusterts, may have salinity or alkalinity in the medium and deep black soils. According to soil taxonomy, almost all the saline and alkali soils can be classified. However, some of the crucial properties in surface horizons of these soils like high ESP and/or EC and criterion for Salorthids are not appropriately explained in the classification (Sharma 1998).

1.3.2 Distribution

Looking at some of the recently modified classifications in the world literature, salt-affected soils are found distributed in all the continents covering about 954.83 million ha (Mha) in about 100 countries, which is about 10% of the total surface of dry land (Szabolcs 1989). As per recent FAO/UNESCO Soil Map of the World (FAO 2008), the total salt-affected area is 835 Mha, out of which 397 Mha are saline and rest sodic soils. Distribution of salt-affected soils excluding magnesium and acid sulphate soils along with countries of occurrence is depicted in Table 1.4.

Table 1.4 Global distribution of salt-affected soils (million ha)

Continent and/or subcontinent	Countries (Szabolcs 1989)[a]	Area (Szabolcs 1989) (million ha)	Area FAO (2008) (million ha)
North America	Canada, USA	15.75	20.0
Mexico and Central America	Mexico, Cuba, Haiti	1.97	
South America	Argentina, Bolivia, Brazil, Chile, Columbia, Ecuador, Paraguay	129.16	112[b]
Africa	Afars and Issas Territory, Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Chad, Cameroon, Egypt, Ethiopia, Gambia, Ghana, Guinea, Kenya, Liberia, Libya, Malagasy Republic, Mali, Mauritania, Morocco, Niger, Nigeria, Senegal, Sierra Leone, Somalia, South West Africa, Sudan, Tanzania, Tunisia, Zaire, Zambia, Zimbabwe	80.54	73
South Asia and the Middle East	Afghanistan, Bangladesh, Burma, India, Iran, Iraq, Israel, Jordan, Lebanon, Kuwait, Muscat and Oman, Pakistan, Qatar, Sarawak, Saudi Arabia, Sri Lanka, Syria, Tanzania, the Trucial States, Turkey, Yemen, the People's Democratic Republic of Yemen	87.61	444[c]
North and Central Asia	China, Korea, Mongolia, Solomon Islands, the USSR (undivided)	211.69	106[d]
South-East Asia	Indonesia, Cambodia, Malaysia, Thailand, Vietnam	19.98	
Australasia	Australia, Fiji	357.33	
Europe	Austria, Bulgaria, Czechoslovakia, Cyprus, France, Greece, Hungary, Italy, Portugal, Romania, Spain, USSRI (partly), Yugoslavia	50.80	80
Total		954.83	835

[a] Does not include magnesium and acid sulphate soils
[b] Mentioned under Latin America
[c] Asia, the Pacific and Australia
[d] Near East

1.3.3 Genesis and Characteristics of Salt-affected Soils

The mineralogical composition of soil, including relative amounts of primary and secondary minerals, is determined by geological processes, the make-up of the parent materials, the intensity of weathering and duration of weathering in the existing soil or the soils that served as parent material for the present soil. Szabolcs (1989) described the genesis of salt-affected soils of many countries showing the effects of relief, mineralogy and climate in different countries. Geologically the

Indian subcontinent is divided into two parts, viz. Peninsula (south of Vindhyans) and the extra-peninsula (mountainous region of Himalayas). Surprisingly, the Peninsula constituting the central and the southern states has been a land area, which since the origin of earth has never been submerged beneath the sea; on the contrary, the extra-peninsula, constituting the northern states of India and the adjacent Pakistan, remained under the saline waters of the sea for greater part of the earth history and has thus been covered by successive marine deposits (Wadia 1979; Raj-Kumar 1998). The greater Indo-Gangetic plains are formed mainly from alluvial deposits of the Indus and Ganges rivers borne down from extra-peninsula, which earlier remained under saline waters of the Tethyan sea. Therefore, there is a basic difference of geology and mineral composition of the northern and southern parts of the subcontinent. Raj-Kumar (1998) has dealt with clay mineralogy of salt-affected soils in detail.

Oceans are the biggest storehouse of salts on the earth's surface. The seawater has 42×10^{15} Mg of dissolved salts, of which 85.65% is sodium chloride. Though the early seas had a very small volume and the water was changed mainly with carbonates of alkali and alkaline earths, the release of huge amounts of water vapours, chlorine and other volatiles from degassing of earth's interior and mantle led to its enrichment with sodium chloride. This happened 100 to 600 million years ago, and since then the seawater is supposed to have maintained composition similar to that prevailing today (cited by Dhir 1998). The rivers on the earth deliver annually 3.85×10^{12} kg soluble salts to the oceans. Of this, the entire sodium chloride content is believed to be cyclic, i.e. goes to land via sea sprays and atmosphere from the oceans, but excess of sodium and rest of the salts owe their origin to the continents (Dhir 1998). However, while the sea is receiving a continuous load of salts from the land, it is also losing it at the same rate through precipitation and other processes, giving seawater more or less the same composition. The rocks and the constituent silicate minerals form the original source of salts on the continents and the oceans. Though 75 to 85% of the igneous rocks are made up of the oxides of silicon, aluminium and iron, the rest are mainly made up by oxides of calcium, magnesium, sodium and potassium. Each of these alkali and alkaline earth elements is present in the range of 2–3% with basalts being in greater abundance of calcium and magnesium and syenites of that of sodium. The elements are concentrated in feldspars and ferro-magnesium minerals.

The previous investigations by several workers (Medlicott 1863; Center 1880; Leather 1914) on *usar* lands of the Indo-Gangetic alluvial plain suggested weathering as a source of presence of salt in these soils. The primary minerals present in the sodic and non-sodic soils of the Indo-Gangetic alluvial plain contain quartz, feldspars (orthoclase and plagioclase), muscovite, biotite, chloritised biotite, tourmaline, zircon and hornblende in their sand fractions (Goswami 1979; Bhargava et al. 1980; Sidhu and Sehgal 1978). Similar types of mineralogy possibly represent the prevalence of plagioclase feldspar in the soils forming part of the alluvium in Punjab (Sidhu and Sehgal 1978; Pundeer et al. 1978).

Studies conducted by several researchers (Agarwal and Mehrotra 1953; Mehrotra 1968; Bhargava et al. 1972; Bhumbla et al. 1973; Sehgal et al. 1973; Bhargava et al. 1980) revealed that the alkali soils occur in micro-depressions of the Indo-Gangetic alluvial plain. Auden et al. (1942) also listed some factors which are responsible for synthesis of the sodium salts such as (a) alternate dry and wet seasons, (b) very gentle slope gradients, (c) rocks rich in soda minerals, (d) quality of ground and canal water, (e) base-exchange reaction and (f) prevailing high water table. First three factors have been justified later by Bhargava et al. (1980), who documented that the weathering of aluminosilicate minerals and the factors of microrelief along with climate inducing seasonal flooding and evaporation of the deposited run-off wash played a significant role in the formation and spreading of alkali soils in the form of local stretches within the micro-depressions.

In the total area of the Indo-Gangetic alluvial plain, alkali soils generally occurred in areas with mean annual rainfall ranging from 550 to 1000 mm (Bhargava and Abrol 1978; Bhargava et al. 1980). Alkali soils in Punjab and Haryana zone mostly occurred in an *ustic* soil moisture regime, however, due to the occurrence of a shallow fluctuating water table, the alkali soils also found existing in an aquic and para-aquic moisture regime in Uttar Pradesh. Some leaching and illuviation processes happen in these soils due to marginal surplus of precipitation over the evaporation, consequences of which lead the formation of illuvial B horizon (Bhargava et al. 1980). The existence of illuvial B horizon has been verified by the occurrence of argillans on ped faces and predominance of finer clay in B horizon, the fine/total clay ratio and existence of clay cutans on ped faces (Sharma 1979; Bhargava et al. 1980). Another effective part played by the predominant climate is to facilitate evaporation of the run-off deposited in the micro-depressions from June to October.

The highly sodic conditions of alkali soils bring about degradation of the clay minerals as noticed by the tendency of differences in molar ratios of amorphous SiO_2 and Al_2O_3 in alkali soil profiles from Uttar Pradesh. Degradation is highest in the surface horizon, declining with depth which is in accordance with the degree of sodium saturation. The geomorphic setting and the physical, chemical and hydrological characteristics of alkali soils establish that these have originated during the direct process of sodiumization beginning firstly at the surface and not through the sequential processes of salinization, alkalization and desalinization (Sharma 1998; Sharma and Bhargava 1981).

Bhargava et al. (1980) and Bhargava and Bhattacharjee (1982) attributed alkaline hydrolysis of feldspars in the upland plains for the origin of soluble salts, which got transported through surface and subsurface flow to sodium spoils and groundwaters in the plains down the gradient. Raj-Kumar (1992), however, contradicted the hypothesis and observed the occurrence of sodic soils and sediments not only on the source area itself but also further up in the Sivalik Hills. Therefore, the salts might have come from further up (Himalayas) and specifically from the marine formations and salt-spring found therein. He further surmised that feldspar weathering was not possible at the prevailing pH of the soils; hence, the sodium carbonate could have come from the reaction of sodium chloride of run-off water with calcareous rocks.

Saline soils occur under different geomorphic and climatic conditions in different parts of the country because different cycles play the most significant role in accumulation of excessive amount of salts in soils. The characteristics of broad groups of saline soils in India, viz. inland, coastal and deltaic saline soils, are discussed by Sharma (1998) below.

1.3.3.1 Inland Saline Soils of Arid and Semiarid Regions

Highly saline soils containing excessive amount of neutral salts are prevalent in the arid to semiarid parts of Punjab, Haryana, Rajasthan and Gujarat. These soils occur in areas receiving < 550 mm mean annual rainfall. Under extremely desiccating conditions, the maximum salts accumulate in the surface horizon. These soils comprise a shallow saline water table and frequently remain waterlogged or even became submerged for some duration in every year. Characteristics of a saline soil with saline and shallow water table are depicted in Table 1.5.

1.3.3.2 Saline-Alkali Soils of Indo-Gangetic Alluvium

The alkali soils are widely spread in the micro-depressions in the parts of Indo-Gangetic alluvial plain and studied well and characterized by several pioneers (Medlicott 1863; Center 1880; Leather 1914; Auden et al. 1942; Agarwal and Mehrotra 1953; Agarwal and Yadav 1954; Govindarajan and Murthy 1969; Kanwar and Bhumbla 1969; Sharma 1979). The most important characteristics of a typical alkali soil pedon are (a) an ochric epipedon with soil matrix and mottle colours in the hues of 2.5 Y or 10 YR; (b) high values and chromas; (c) textural gradation from sandy loam in the epipedon to clay loam or clay in the B horizon; (d) platy structure in a few surface centimetres followed by subangular/angular blocky structure below, ultimately turning massive in the calcic horizon usually about 1 metre deep; (e) presence of Fe/Mn concretions in the B horizon (normally throughout the depth above the calcic horizon); (f) very low organic matter status, decreasing gradually with depth; (g) preponderance of carbonates and bicarbonates of sodium; (h) gradual decrease of ECe, pH, ESP and SAR with depth; (i) low to very low infiltration characteristics; and (j) occasional presence of fluctuating, good-quality, shallow underground water table (Bhargava and Abrol 1978).

These soils exist, mostly in regions where mean annual rainfall is ~ 550 to 1200 mm, in the form of a narrowband separating the saline and alkali soils. These soils have a predominance of neutral salts and, however, also have sizable amount of sodium carbonates and bicarbonates. These are sandy to loam in texture and may contain a calcic or a petrocalcic horizon in the subsurface. The most of the alkali soils in this region are with dominant anionic composition of dissolved salts as $CO_3 + HCO_3 > Cl = SO_4$. Among the cations, sodium is by far the most dominant,

Table 1.5 Saline soil underlain by saline groundwater from Kalayat, district Jind (Haryana)

Depth (cm)	pHs	ECe (dS m^{-1})	ESP	CO_3^{2-} + HCO_3^- (meq L^{-1})	Cl^- (meq L^{-1})	SO_4^{2-} (meq L^{-1})	Na^+ (meq L^{-1})	Ca^{2+}+Mg^{2+} (meq L^{-1})	$CaCO_3$ (%)
0–14	7.8	65.5	7	2.3	588	95.0	538	89.0	0.4
14–29	7.6	18.1	8	2.0	146	42.0	151	47.0	Nil
29–67	7.7	9.4	8	1.5	72	24.5	75	20.5	0.3
67–105	7.6	8.0	7	1.8	61	25.0	49	35.2	1.6
105–140	7.7	5.0	8	3.0	30	15.5	36	16.5	0.8

Source: Bhargava (1989)

and sodium adsorption ratio (SAR) of saturated extract is often in the range of 20 to 70 mmol L^{-1}. The mean profile ECe is highly variable, mostly in the range of 2–10 dS m^{-1} (Bhargava 1989). The saline-alkali and saline soils have higher-profile salinity and have generally NaCl and occasionally Na_2SO_4 as the dominant salt.

Weathering of aluminosilicate minerals during carbonation released solutions of bicarbonates and carbonates of alkali besides colloidal form of silica and alumina. The amount of sodium release increases in rate at temperatures greater than 25 °C. The bicarbonates and carbonates of alkali migrate along with subterranean and surface waters and deposited in undrained region under semiarid climatic conditions to form alkali soils (Kovda 1964).

$$\begin{aligned}
&\text{Na-primary mineral} + \text{HOH} \rightarrow \text{H-silicate clay} + \text{NaOH} \\
&\text{H-silicate clay} + \text{HOH} \rightarrow Al_2O_3.H_2O + H_2SiO_3 \\
&NaOH + CO_2(\text{air}) \rightarrow NaHCO_3 \\
&NaHCO_3 \rightarrow Na_2CO_3 + CO_2 + H_2O
\end{aligned}$$

1.3.3.3 Inland Saline Soils of Subhumid Region

Large area of subhumid parts of north Bihar has experienced secondary salinization under the influence of continental climate and anthropogenic cycles. These soils are prevalent in parts of East Champaran, West Champaran, Saron, Muzaffarpur and Saharsa districts and developed on dolomitic alluvium having 23 to 40% calcium and magnesium carbonates in fine form. Though neutral salts dominate in these soils, some saline-alkali nature soils also have sizable content of sodium carbonate and bicarbonate.

1.3.3.4 Inland Salt-affected Medium and Deep Black Soils (Vertisols)

The medium and deep black soils (Vertisol) are widespread in parts of Madhya Pradesh, Maharashtra, Rajasthan, Andhra Pradesh, Gujarat and Karnataka. All Vertisols have the possibility to turn into saline, alkali or saline-alkali, and all these may occur within a small geographical area. The processes of salinization and alkalization are linked with rising water table successive to installation of canal irrigation in Vertisols. Montmorillonitic (smectite) clay mineralogy and high amount of clay content impart adverse physical characteristics to these soils.

1.3.3.5 Medium to Deep Black Saline Soils of Deltaic and Coastal Semiarid Region

Saline Vertisols with shallow water table existing generally within 1 metre depth in the deltas of the Godavari and Krishna rivers and along the Saurashtra coast in Gujarat. These soils usually have only neutral salts, with very small amount of bicarbonates. Smectite clay mineralogy and high content of clay create problems comparable to the inland saline Vertisols.

1.3.3.6 Saline Micaceous Deltaic Alluvium of Humid Region

The deep micaceous and fine-textured soils of the Ganges delta under humid subtropical climate region are saline to varying magnitudes, with a continuous shallow saline water table. These soils contain neutral salts, which owe their cause to saline substratum and saline water inundations during the time of marine cycles and also in the time of the origin of delta. These soils comprise (a) an ochric epipedon, (b) yellowish brown mottles, (c) uniformly fine texture ranging from clay loam to clay or silty clay and (d) neutral to slightly acid pH. These soils contain the maximum salt deposition in the surface horizon and show predominance of chlorides and sulphates of sodium, calcium and magnesium with small content of bicarbonates, but $CaCO_3$ is not present. The horizon lying immediately beneath the plough layer in these soils consistently becomes very hard due to deposition of silica and operation of frequent rice cropping (Sharma 1995). Characteristics of a typical soil profile are given in Table 1.6.

1.3.3.7 Saline-humic and Acid Sulphate Soils of Humid Tropical Regions

These saline soils are humus-rich and exist in marshy situations along the Malabar Coast. These undergo fresh water submergence from the month of May to December and seawater inundation in tidal cycles for the duration of following lean months. These soils possibly developed under the influence of marine cycle. The salient characteristics of these soils are (a) ochric epipedon; (b) humic horizon in the substratum of some soils; (c) a variety of soil matrix colours varying from pale yellow to very dark grey, greyish brown and dark yellowish brown; (d) signs of gleying, reduction and bleaching in the soil matrix; (d) high EC throughout the profile; (e) soil pH in the acidic range; and (f) high to very high contents of organic matter and a shallow saline water table (Sharma 1998). Occurrence of pyritous clay on Malabar Coast and the variations in soil pH from 3.5 to 7.5 can be attributed to uneven distribution of pyritous clays in the alluvium (Wadia 1966). Characteristics of a typical soil profile are presented in Table 1.7.

1.3.3.8 Saline Marsh of Rann of Kutchh

The great Rann of Kutchh comprises the extensive saline marshy area and has a variety of saline soil types. The process of accumulation is persisting, and textural stratifications are intermixed with bands of gypsum, calcium carbonate and hydrated iron oxide deposition and thus make easy the classification of separate taxonomic units.

A distinct, regular and thick zone of $CaCO_3$ accumulation, mostly dolomitic (Sharma and Bhargava 1981), exists around 1 metre depth from the surface in alkali soils. Sehgal and Stoops (1972) documented that the smooth boundary of the calcic horizon, irregular shape of individual concretion and regularity of existence beneath vast areas draw attention to their pedogenic origin. The zone of calcic horizon probably points out to the zone of shallow water table fluctuation, while recession of water table tends to concentrate the soil solution, and the calcium and magnesium come first to precipitate irreversibly as carbonates. With repetitive hydrological cycles, the precipitates persist to grow in size and occlude the various kinds of soil material (Sharma 1998; Sharma and Bhargava 1981).

Table 1.6 Saline deltaic soil from Sundarbans in 24 Parganas district (West Bengal)

Depth (cm)	pHs	ECe (dS m^{-1})	ESP	CO_3^{2-} + HCO_3^- (me L^{-1})	Cl^- (me L^{-1})	SO_4^{2-} (me L^{-1})	Na^+ (me L^{-1})	Ca^{2+}+Mg^{2+} (me L^{-1})	Clay (%)	$CaCO_3$ (%)
0–12	7.2	27.4	30	0.8	313.4	16.5	156.4	139.1	34.0	Nil
12–80	7.5	7.6	14	1.0	65.5	8.6	40.9	30.4	45.2	do
80–105	6.7	7.5	16	1.2	74.5	9.6	48.5	31.7	46.4	do
105–162	6.4	9.2	21	0.6	98.4	8.3	71.7	44.8	39.3	do
162–184	6.9	10.4	21	0.5	96.2	11.4	74.7	46.1	44.7	do

Source: Bandyopadhyay et al. (1988)

Table 1.7 Saline, acid sulphate soils from Arikum in Calicut district (Kerala)

Depth (cm)	pHs	ECe (dS m^{-1})	ESP	CEC (me 100 g^{-1})	Ex. H (me L^{-1})	Ca^{2+}+Mg^{2+} (me L^{-1})	Na^{+} (me L^{-1})	Cl^{-1} (me L^{-1})	SO_4^{2-} (me L^{-1})	Clay (%)	O.M. (%)
0–9	4.4	43.6	6.4	18.7	2.2	123	322	354	120	47.6	4.8
9–20	4.8	12.6	5.8	20.4	1.2	38	100	105	36	38.8	3.6
20–36	4.8	11.7	6.8	14.7	1.2	44	82	86	53	46.0	2.4
36–70	4.5	8.4	11.1	26.1	1.2	25	76	57	65	63.4	2.6
70+	3.4	38.6	20.5	69.2	18.7	112	285	337	75	50.2	40.5

Source: Bandyopadhyay et al. (1988)

1.3.3.9 Other Categories of Alkali Soils

1.3.3.9.1 Indo-Gangetic Plains

Some other groups of alkali soils which are slightly different from those mentioned above do occur in various parts of the country. These soils may infrequently have a calcic horizon within 50 cm depth from the soil surface. The existence of a shallow calcic horizon is due to either shifting of the surface soil by extreme erosion or deposition of dolomitic material at lower depths because of insufficient leaching. The major characteristics, limitations and ameliorative measures of these soils are comparable to those soils which have a calcic horizon at 1 m or more depth. A shallow calcic horizon has decreased depth of soil for root proliferation and low ability to reserve nutrient and water. Alkali soil with a saline groundwater also occurred in narrow bands in Punjab, Haryana and Uttar Pradesh in regions having 500–700 mm annual rainfall. Shallow saline or alkali groundwater when increased to within 1 m depth triggers the existing sodic conditions (Sharma 1998).

1.3.3.9.2 Black Alkali Soils of Deccan Plateau

The colours of soil matrix vary from grey to very dark grey, dark to very dark greyish brown in the surface horizons and black to dark grey and dark greyish brown in the subsurface horizon. Generally, clay or clay loam soil texture is found, with major parts of subangular blocky structure. These soils have narrow range of workable moisture due to higher stickiness, plasticity and cohesiveness and thus upon drying become very hard and make tillage operation impossible. Moreover, very slow permeability and infiltration is another serious problem in alkali Vertisols. Black soils (Vertisols) also develop deep cracks on drying, because of high coefficient of swelling and shrinkage due to montmorillonitic clays. Smectite particles become deflocculated faster under high degree of sodium saturation and high pH, consequently disintegration of soil aggregates and sealing of pore space take place. Under a buildup of shallow water table environment, high capillary conductivity makes possible rising of water to the soil surface, rendering it extremely moist, saline and unworkable. High pH unfavourably affects solubility and bioavailability of cationic micronutrients, causing severe nutritional disorders. Deficiency of phosphorus is unlikely, because of enhanced solubility of sodium phosphate. Contrary to alkali soils of the Indo-Gangetic alluvial plains, pH and salinity of these soils differ, irregularly and indicative of different phases of alkalization and salinization. These variations are linked with rising water table. The degree of problem becomes more severe, when surface horizons comprise a higher value of pH and high content of salt rather than when these situations exist in subsurface horizons (Bhattacharyya et al. 1994; Sharma 1998).

With regard to alkali Vertisols, the hydraulic properties of soils rely upon the clay mineralogy, ESP of the soil and the concentration and nature of electrolytes in soil solution. The Vertisols of Western India having ESP of approximately 15 comprise extremely poor soil physical properties which makes tillage operations very difficult (Bhattacharyya et al. 1994). Some worker recommended a significantly lower ESP (6) for rating soils to be alkali soils particularly those with a plenty of fine clay and be deficient in soluble weatherable minerals (Northcote and Skene 1972; Shanmuganathan and Oades 1983). Balpande et al. (1996) also recommended an ESP limit of 5 for alkali subgroup of Vertisols in Central India which have high amount of smectite clay mineral (491 g kg^{-1}) in the soil control section. Smectites are considered as high-swelling clays, particularly when Na-saturated (Low 1980). These consist high percentage of clay, exchangeable sodium and cation-exchange capacity. Sodium is mostly dominant throughout the soil depth, but bicarbonate dominates in the deeper layers. Soil salinity and soil pH rise with soil depth. Calcium carbonate exists throughout the soil profile (Sharma 1998). Characteristics of some typical soil profiles are shown in Tables 1.8 and 1.9.

1.4 Historical Perspectives of Management of Salt-affected Soils

In different salt-affected areas of the world, under different natural and economic conditions, countless approaches and methods exist for the utilization and reclamation of these soils. To give the details of these approaches is not the scope of this chapter (many aspects are dealt in different chapters of this book). However, we require different approaches for reclamation and management of alkali and saline soils. Alkali soils are reclaimed mainly by application of amendments such as gypsum, phosphor-gypsum, pyrites, etc. to lower down the pH, while in saline soils the salts are removed from the site through proper drainage (see Szabolcs 1989; Minhas and Tyagi 1998; Dagar 2014; Dagar and Minhas 2016). In both cases biological approaches are also effective. In this chapter some historical perspectives are mentioned in adopting the reclamation approaches.

The earliest research studies conducted on reclamation/bioremediation of alkali soils include series of experiments by Kelley and his associates in California in the 1920s and 1930s (Kelley and Brown 1934; Kelley 1937, 1941, 1951; Kelley et al. 1940). The soil (Natric Durixeralf) of experimental site was fine sandy loam solonetz located on the Kearney Ranch near Fresno having chemical properties in upper 30 cm layer: pH 9.2–9.7, $EC_{1:5}$ 6.1–7.2 dS m^{-1}, CEC 43–44 $mmol_c$ kg^{-1} and ESP 57–70. The soil was uniform in texture to a depth of 60–90 cm, below which there was a compact calcic (mainly $CaCO_3$) layer of 5–15 cm thick. In first phase (in 1920–1921), 37 Mg ha^{-1} gypsum was applied as amendment in two splits (22 kg in 1920 and 15 kg ha^{-1} in 1921). The gypsum application was followed by flooding with well water (EC 0.3 dS m^{-1}, SAR 0.7) and submerged for 3 weeks. The same amount of well water was applied to the bioremediation treatments with adoption of barley (*Hordeum vulgare*) cultivation for 2 years followed by green manuring by Indian sweet clover (*Melilotus indicus*) and white sweet clover (*Melilotus alba*) and a 5-year cultivation of alfalfa (*Medicago sativa*). After alfalfa, the plots were kept fallow for 1 year and then cultivated with cotton (*Gossypium hirsutum*) as first post-reclamation crop. The cotton yields were 1.82 and 2.10 Mg ha^{-1} for gypsum and bioremediation treatments, respectively. Exchangeable sodium percentage of upper 30 cm soil decreased from 70 to 5 in gypsum-treated soil and from 65 to 6 in

Table 1.8 Physico-chemical characteristics of typical alkali soils

Depth (cm)	ECe (dS m^{-1})	pHs	ESP	Ionic composition (me L^{-1})						Particle size analysis (%)			CaCO$_3$ (%)	CEC (me 100 g^{-1})
				Ca^{2+}	Mg^{2+}	Na$^+$	CO$_3$$^{2-}$	HCO$_3$$^-$	Cl$^-$	Sand	Silt	Clay		
(a) Alluvial soil region (Etah, Uttar Pradesh)														
0–16	13.84	10.2	88	0.6	1.6	210	151	28	14	62.0	24.0	14.0	1.9	6.7
16–27	12.50	10.1	87	1.1	1.4	190	129	20	14	57.0	25.5	17.5	4.0	7.3
27–64	4.60	9.7	67	0.5	0.8	45	32	10	11	45.0	22.0	33.0	3.8	15.9
64–81	1.92	9.8	78	1.0	1.5	19	4	13	5	38.0	35.0	27.0	2.7	13.9
81–108	1.88	9.4	24	0.5	1.5	16	4	9	6	34.0	34.0	32.0	12.0	12.9
108–127	2.35	9.1	31	0.5	0.5	21	7	10	6	39.5	33.0	27.5	23.8	12.0
127–148	1.40	8.6	22	1.3	1.4	13	2	6	6	65.0	18.0	17.0	25.0	8.0
(b) Vertisol (Shajapur, Madhya Pradesh)														
0–13	3.5	8.3	60	5.1	5.1	26	Nil	6.3	23.0	15.5	50.0	34.5	8.0	12.0
13–31	1.7	8.4	65	4.2	1.0	8	Nil	9.2	9.0	30.0	45.5	29.5	7.0	12.8
31–62	2.8	8.2	73	2.1	4.8	14	Nil	14.2	8.8	3.0	56.0	42.0	12.8	27.0
62–94	1.6	9.4	51	2.2	4.9	8	Nil	10.2	8.1	4.0	52.5	43.5	21.2	19.0
94–126	6.5	9.1	51	6.1	8.8	59	Nil	87.0	21.0	7.0	46.0	47.4	21.4	25.0
126–158	2.5	8.7	56	2.9	5.1	18	Nil	8.8	10.8	3.0	54.0	48.0	18.7	17.7

Source: Sharma (1998)

Table 1.9 Physico-chemical properties of soils at Panipat district (Nain farm) of Haryana

Depth (cm)	pHs	ECe dS m^{-1}	Na^+ (me L^{-1})	K^+ (me L^{-1})	Ca^{2+} + Mg^{2+} (me L^{-1})	HCO_3^- (me L^{-1})	Cl^- (me L^{-1})	SO_4^{2-} (me L^{-1})	OC (%)	ESP (%)	$CaCO_3$ (%)	CEC cmol kg^{-1}	Sand (%)	Silt (%)	Clay (%)
Pedon 1: 29°19′04.1″N and 76°47′55.1″E, coarse loamy, mixed sodic Haplustepts, grasses, *Prosopis juliflora* grown, water table depth <2.5 m															
0–16	9.0	58	1217	5.7	10	2.0	500	71.9	0.45	30.9	2.1	10.6	81.4	13.0	5.5
16–42	9.4	31	659	0.6	7	1.5	240	69.5	0.30	43.9	1.4	8.0	57.5	25.1	17.4
42–77	9.5	13	243	0.01	5	1.5	95	56.3	0.27	44.0	1.3	14.5	58.3	20.7	20.9
77–112	9.6	10	183	0.1	5	2.0	75	20.9	0.18	54.0	1.9	13.0	63.8	18.8	17.3
112–150	9.7	10	207	0.1	5	2.0	69	19.2	0.22	55.3	10.1	11.5	59.2	25.2	15.5
150–180	9.6	11	234	0.1	5	2.0	77	25.8	0.19	58.0	13.2	20.4	39.9	34.9	25.1
180–220	9.5	15	301	0.1	5	2.0	92	30.5	0.24	55.0	15.1	22.8	48.8	27.6	23.5
Pedon 2: 29°19′02.9″N and 76°47′50.3″E, fine loamy, mixed Typic Haplustepts (saline phase), *Prosopis juliflora* grown, water table depth <3.5 m															
0–23	8.5	71	1908	1.0	48	0	500	71.8	0.34	25.0	1.2	13.6	68.6	18.9	12.3
23–73	8.2	45	1241	0.5	45	1.5	240	71.1	0.31	20.0	1.3	13.9	58.6	21.8	19.5
73–110	8.4	20	406	02	17	1.5	95	68.6	0.22	29.0	1.6	19.7	54.8	20.1	25.1
110–145	8.5	21	273	02	20	2.0	75	66.4	0.28	21.2	2.1	12.1	54.1	24.3	21.6
145–170	8.1	23	469	01	41	2.0	69	64.5	0.22	29.5	8.8	16.6	70.0	16.2	13.8
170–192	8.7	25	469	0.1	63	2.0	77	59.9	0.24	33.3	9.0	19.7	55.8	25.7	18.4
192–252	8.7	19	336	0.1	55	2.0	91	64.3	0.25	37.5	10.2	14.7	48.0	35.4	16.5
Pedon 3: 29°19′04.5″N and 76°47′42.4″E, coarse loamy, mixed Sodic Haplustepts, partly barren, grasses grown, water table depth >5 m															
0–20	10.0	82	2577	3.0	5	5.5	775	126.5	0.25	77.1	2.52	9.8	68.5	20.5	10.9
20–60	9.5	28	505	0.4	6	1	210	69.5	0.27	68.8	1.05	11.4	59.5	23.2	17.2
60–85	9.0	14	257	0.1	17	0.5	87	56.3	0.24	50.0	1.89	10.4	58.3	20.8	20.8
85–132	8.9	13	248	0.1	19	0.5	75	54.5	0.24	57.0	6.51	11.7	59.1	23.5	17.2
132–158	9.0	19	414	0.2	29	1.5	118	53.0	0.25	60.4	7.77	12.1	55.4	29.7	14.8
158–175	9.0	21	381	0.1	32	1	130	69.9	0.24	56.4	12.82	7.3	40.6	43.2	16.0
175–229	8.9	17	269	0.2	33	1	97	64.7	0.24	45.9	16.17	9.8	34.1	47.2	18.5

Pedon 4: 29°19′08.4″N and 76°47′34.8″E, coarse loamy, mixed Typic Haplustepts, grasses and *Prosopis juliflora* grown, water table depth >5 m															
0–22	7.7	14.1	174	1.0	49	3	86	64.1	0.49	16.4	1.1	12.2	62.0	21.2	16.7
22–53	8.0	21.3	273	0.8	51	2	134	65.6	0.28	19.9	0.2	7.5	65.1	19.9	14.8
53–85	8.0	25.3	321	0.9	50	1.5	166	68.9	0.18	34.9	0.2	6.7	60.5	19.7	19.7
85–117	8.2	25.4	326	0.8	60	2	176	67.4	0.18	40.9	1.1	5.74	57.1	30.8	11.9
117–160	8.4	21.3	274	0.7	52	1	140	68.1	0.18	23.8	6.1	8.00	57.1	26.2	16.6

Source: Mandal et al. (2013)

bioremediation plots. In the second phase (1930–1937), also under bioremediation [with Bermuda grass (*Cynodon dactylon*) for 2 years followed by barley for 1 year, alfala for 4 years and oats (*Avena sativa*) for 1 year], the ESP values of upper 30 cm soil reduced from 57 to just 1 after 8 years (Kelley 1937; cited by Qadir and Oster 2002). Similar bioremediation results were also obtained in irrigated meadow experiments at Bekescsaba, Hungary (de Sigmond 1923, 1924, 1927), and at Vale, Oregon (Wursten and Powers 1934). The last major reclamation effort in California was along the west side of the San Joaquin Valley brought under irrigation during the 1950s and 1960s. Cropping during reclamation was a common practice, and chemical amendments such as gypsum, sulphur and sulphuric acid were used selectively (Kelley 1941, 1951). Barley, a winter crop, was usually the first crop during reclamation followed by cotton and other crops.

Alberta Agriculture (1979) reported that the extent and severity of saline seeps are increasing in Western Canada and the North Great Plains at a rate of 5% per year. In Montana, the rate of increase in salt-affected areas was also found to vary from year to year depending on the climate. An Albertan survey on the Peigan Indian Reserve showed a threefold increase in saline seep acreage on cultivated land over a period of 10 years from 1961 to 1970 (Vander Pluym 1978). Cannon and Wentz (2000) used the historical data of over a 55-year period covering large areas in aerial photography and found the technique most reliable in central and southern Alberta. A series of air photos were used by them to determine the extent of visible salinity for each decade since 1950 for 89 sites in the brown, dark brown and black soil zones in Alberta. Total visible salinity for all sites fluctuated considerably over the monitored 50-year period. The results were similar to Harker et al. (1996) who monitored 55-year data for southern Alberta.

The farming history of salt-affected soils of the Indian subcontinent reveals that most farmers typically began reclamation during the high rainfall months (July to September) resulting in considerable leaching and reclamation. Singh (1998a) tried to connect the entire historical account of reclamation which has been briefed here. In the Indian subcontinent, as early as 1879, a *Reh* (salinity) Committee was constituted to deliberate on the origin of salts in soils. HB Medlicott, Director, Geological Survey, and a major contributor member of the committee, elaborated on two important sources of salts in soils, i.e. weathering of soil constituents and role of canal water irrigation. As per his statement, '*Reh* is formed of highly soluble sodium salts resulting from decomposition of the rock minerals by air and water'. Being the waste product of soil formation, *Reh* itself generally occurs in soils due to 'elements unassimilated by vegetation and their gradual removal as a consequence of the rain water draining through the soil and carrying with it any excess of these highly soluble salts'. On the contribution of canal water, Medlicott emphasized that it was a perpetual independent and an inexhaustible source of salts. Sir EC Buck, in his note to the *Reh* Committee, described the role of wind in picking and depositing salts. Similarly, FN Wright also suggested the role of winds blowing over places covered with salt efflorescence and salt deposition in the adjoining fields in hot months. Wright further noted the rise in water level in the vicinity of the canal and thus reaffirmed the assertion of Medlicott on the role of canals in soil salinization.

Though *Reh* committee discussions did not lead to any conclusion on the theory of alkali formation in soils, the views of Medlicott seem to have prevailed. Another outcome was that a scheme of experimental work was drawn up, to be carried out mainly by the newly formed agricultural department (Singh 1998a).

1.4.1 *Reh* Committee Recommendations and Their Follow-up (Singh 1998a)

The *Reh* Committee recommendations were mainly directed towards preparing the soil for profitable cultivation adopting practices for removal of salts, proper drainage, avoiding silting, deep cultivation, adequate manuring and ploughing of green crops. To decide the course of action for the reclamation of salt lands, a conference was held in 1879 at Aligarh. The main decisions of the conference, as documented by Leather (1897), were the following:

- Prepare *Reh* maps to ascertain *Reh* distribution throughout the provinces, and study its variations over the years in certain selected villages. Accordingly, the maps were prepared, and a series of observations were made in 65 villages of Akbrabad pargana in Aligarh district.
- A survey of subsoil waters showing depth to water table was done, and a surface drainage map was also prepared for the same villages of Akbrabad. A number of agricultural experiments were started at Awagarh, Aligarh and Kanpur.
- The effect of surface drainage was tested by erecting small embankments and allowing rainwater to leach them. According to Leather, the experiment appeared to have been a failure. Likewise, 2-inch pipes were laid in another plot, but the pipes silted up, making the experiment fruitless. Similarly scraping the *reh* off the surface also proved quite useless.
- Near Aligarh, another experiment on reclamation of *usar* was started with land enclosure and planting of trees. Plantations were also grown at other locations in Aligarh and Kanpur districts. Variable success was observed with use of manure along with initial leaching through embankments of plantations and grassland. Crops like barley and peas in *rabi* and at some places rice in rainy season (*kharif*) were cultivated in these experiments. The lands showing improvement were later leased.

Greig (1883), after visiting one plantation at Purdilnagar near Sikandra Rao in the Aligarh district and seven plantations near Awagarh, made some important observations on the heterogeneity in salt lands. He recorded that a simple and reliable way of finding good patches in a *usar* plot was to stop grazing for a year and then examine the ground. *Dub* (*Cynodon dactylon*) and other grasses appeared on good patches, but only one kind of grass that was not found on any other soils grew on highly *reh*-impregnated soil (may be *Desmostachya bipinnata*). According to him in real *usar*, the trees only did well if the pits filled with good soil were deep enough to let the roots extend beyond 90 to 120 cm of *reh* into a less deteriorated soil below. These observations formed the basis of the auger-hole method of planting trees in alkali soils later advocated by the Central Soil Salinity Research Institute, Karnal.

JA Voelker, in 1891, observed that the results of the experiments were not supported by analysis of experimental site soil and thus it was difficult to make an accurate opinion about their application to other *usar*-affected lands (cited by Moreland 1901). For better understanding of these investigations, JW Leather was included as agricultural chemist in the staff of the Imperial Department. Consequently, after thorough investigations of reports of experimental farms at Amarmau and Juhi in Kanpur district and Chherat and Gursikran in Aligarh district, Leather (1893) described causes of accumulation of salts, the effects of canals and details of reclamation methods followed by the farmers and the experiments carried out under the scheme of *Reh* Committee.

1.4.2 Reclamation Experiments (Mostly Based on Reported by Singh 1998a)

1.4.2.1 Sind Area

The *usar* reclamation was first commenced at Mirpur Khas, Daulatpur and Sukkur on two major soil types, i.e. the clayey soils near river Indus and its old branches and the coarse-textured soils. Henderson (1909) observed that no crops were growing on a part of Mirpur Khas farm because of varied presence of the salt content (0.08–0.98%) with dominance of sulphates in different plots. Continuous ponding of 5 cm water for 4 to 5 months followed by sowing of Egyptian clover, cotton, pearl millet and Sindhi cotton in different years helped in reclamation of salty soils at Sukkur and Mirpur Khas (Henderson 1909). The work was started in bad *kallar* site with chloride-dominant salt content ranging from 0.1% to 1.54% at Daulatpur in the beginning of 1908. The land was levelled and drained to wash down the salts into subsoil and repeated growing of Egyptian clover (Henderson 1914). Sind experiments suggested importance of Egyptian clover and rice in reclamation of all hues of salt-affected soils in Sind and Punjab.

Commissioning of Sukkur Barrage, in highly salt-impregnated finer texture soil with brackish groundwater and poor drainage areas in Sindh, was supposed to create large-scale irrigation potential and consequent simultaneous new problems as experienced elsewhere. To better understand the processes responsible for soil degradation and its productive use in advance, a committee presided over by the Commissioner of Sind in Karachi early in 1924 recommended the establishment of a first-class agricultural research station at Sakrand in a typical canal-irrigated area (Mann 1927). The Sakrand experiments were planned mainly to answer the questions like development of soil salinity, possible loss in soil fertility, danger of waterlogging, etc.

1.4.2.2 Punjab

Though the first official notice of soil salinity in canal commands of India came from the eastern part of the then Punjab, it was the western part that faced the real threat, so much so that the land allottees in Rangpur and Mailsi canal commands abandoned their lands because of the 'white devil'. The standard practice of growing rice-Egyptian clover rotation for reclamation did not succeed everywhere, and some soils of Sindh needed gypsum application for their reclamation (Henderson 1914). This kind of land treatment was more important in so-called *bara/bari* soils first encountered in the Bari Doab of Punjab, the area between Beas and Ravi rivers. The distinction between saline and alkali soils for the purpose of treatment was made only on the basis of their physical traits like hardness and permeability to water. Analysis of soils formed the basis of diagnostics tool for distinction of salinity and alkalinity only after joining of Mr. JH Barnes as first agricultural chemist to the Punjab government in 1906. The importance of the scientific investigations on *reh* can be judged from excerpts of regrets for noncompletion of the chemical laboratory at Lyallpur in the 1909 report of the Joint Secretary to the Financial Commissioner, Punjab. The Joint Secretary further hoped that the agricultural chemist would be able to make some headway with his necessary preliminary investigations in the following year. An important step of formation of a small committee was taken at the 1909 agricultural conference of Nagpur. This committee was entrusted the task to ensure the proper coordination of the work on *reh*, which is being undertaken in most of the Provinces in India, and the consequent acceleration of practical results from through scientific investigations.

At the instance of Barnes, the Punjab government in 1908 surveyed the Lower Chenab command area to investigate the extent of salt problem. Waterlogging had been noticed in the new canal commands of Punjab which also caused soil salinity. Mr. Barnes initiated reclamation experiment at Narwala in 1915. His studies on deep cultivation, drainage and salt washing successfully reclaimed soil which was restored to original owners. He proposed a similar alkali reclamation scheme for the Lower Bari Doab command just before his unfortunate demise (Mackenna 1918). Nevertheless, the Punjab government was so impressed by the success of Narwala reclamation work that a scheme was sanctioned to reclaim crown lands in Lower Bari Doab Canal commands on a 663 ha area with various levels of deterioration. Simultaneously, pot experiments were laid on *bara* soil at Pusa. Barnes and Ali (1917) and later Nasir (1923) used gypsum to study the increase in ammonification activity of soil micro-organisms in alkali soils. Use of gypsum with the clear objective of replacing exchangeable sodium of the soil by calcium in amendment started only when the scientists clearly understood the phenomenon of cation exchange. Comparison of calcium chloride and gypsum for this purpose by Singh and Nijhawan (1932) and Puri (1934) was a landmark research effort in this direction.

1.4.2.3 Black Soil Region

Based on the Nira Valley Expert Committee (1903) recommendations and November 1905 resolution of the Revenue Department, experiments on amelioration of salt lands of the Nira Valley were initiated under the supervision of Mr. Knight in 1908. Mann and Tamhane visited these experiments in 1909; examined water samples from river, canal and the holes dug in the soil; and concluded that salty subsoil water within 1.5 m depth existed throughout a large part of Nira canal area (Mann and Tamhane 1910). They cautioned that a slight error on the part of the cultivators could bring these salts to the surface and ruin the land. They concluded that salt land in the Nira canal command was due solely to the raising of the water level as a consequence of the existence of the canal in the area. The area under barren lands was increasing in almost all canal-irrigated areas with accumulation of salt in variable degrees, and as regards control measures, it was suggested that deepening of main drainage channels, chiefly *nalas*, could prevent extension of the problem. The restriction of water would lower the subsoil water level, and withdrawal of water from the area could lead to gradual recovery, especially where salt buildup had just begun. They proposed that digging at least 75 cm deep drains across the line of natural drainage of the land with an adequate outlet and then thorough salt washing by frequent irrigations after bunding the land was only successful method of recovery of barren lands. However, in his comments on the bulletin by Mann and Tamhane, Leather (1911) asserted that no system of drains that ran only across the lines of natural drainage could possibly be effective either in the Deccan or elsewhere. In fact, he gave considerable value to reclamation work comprising minor drains, running across the direction of natural flow, and a major drain, running in the direction of natural flow into which the minors emptied.

To manage the problem of waterlogging and salt buildup, noticed in the tank-irrigated areas of southern India, a number of experiments on stone and tile drains were initiated at Saidapet in Madras Presidency by Robertson in 1873. His observation of silting of drains despite using collars warranted more research to sort out the problem. Wood (1914) reported work on subsoil drainage to reduce soil salinity of rice lands under tank irrigation of the central farm, Coimbatore. His experiments included two kinds of drains, i.e. plain loose stones and tar dipped end-to-end threaded long bamboo tubes laid in 1910 and worked up to 1914. In other experiments stone drains laid in ‘alkaline’ rice land had been running for 5 years and making the land fertile. Wood (1914) considered these experiments a financial success.

1.4.3 Post-independence Reclamation

1.4.3.1 Sharda Sahayak Canal Command Area

Sharda Sahayak Canal, commissioned in 1978 to provide irrigation to 1.67 million ha area in 21 districts of Uttar Pradesh in northeast India, markedly increased agriculture productivity in the command area. However, absence of drainage and continuous seepage from the canal resulted in a rise in water table and subsequent upward flux of salts to the surface soil layers inflicting salinity in ~ 0.37 million ha area in a span of three decades. Out of this, nearly 0.15 million ha area has been estimated as sodic (higher concentration of sodium carbonate and sodium bicarbonate in the profile) with shallow water table. The present scenario is that more than 1 km area adjacent to both sides of the canal has gone out of cultivation and the farmers have almost abandoned their lands. In extreme cases, mango plantations of more than 20 years old started withering and drying (Singh 2009).

1.4.3.2 Indira Gandhi Nahar Project (IGNP)

IGNP earlier known as Rajasthan canal project was launched to provide drinking and irrigation facilities to 1.79 million ha area in the districts of Ganganagar, Hanumangarh, Bikaner, Jaiselmer, Jodhpur, Barmer and Churu in the arid north-west tract of Rajasthan. The IGNP command area receives an annual rainfall of 30 cm in feeder canal area to less than 12 cm in Jaiselmer area, while the potential evaporation varies from 160 to 200 cm per annum. As such the soils of the region can be divided into the floodplain soils (54% of the area) and aeolian soils (46% of the area). The floodplain soils are mainly fine sandy, deep calcareous, highly stratified loams with good water-holding capacity, with roughly 10% being saline or moderately alkaline. The aeolian soils, in general, are coarse textured, deep and calcareous with low fertility and are highly susceptible to wind erosion. Soils in Jamsar, Lunkaransar, Soorsar, Dattor, Sallor distributory and Khusar minor and Mohangarh are gypsiferous. The gypsiferous soils are in general shallow and found in intra-dunes flats at low-lying areas. Due to the presence of a hard and impervious layer, its management is difficult. The introduction of irrigation in desert area brought about a mini green revolution and considerable prosperity to the farmers. Some of the positive impacts of the introduction of irrigation in the desert included improvement in microclimate, change in land use and in cropping pattern and improvement of soil and moisture conditions and associated biological activities in the soils. However, few years after the introduction of irrigation, several negative effects such as rise in the water table, waterlogging, formation of marshy lands, increased soil salinity and decreased biodiversity also emerged. The current estimates indicate that about 0.18 million ha land is already affected by salinity and sodicity in IGNP command. The salt-affected soils in this command are mainly located in Anupgarh branch, Suratgarh branch and Eastern block. Because of poor infiltration rate, high bulk density, poorly developed structure, stratification and hard crust formation in the soil, the maximum area under salinity/sodicity is in Anupgarh branch. The soils are predominately clay to silty clay with blocky structure and are thus difficult to cultivate when dry and remain wet for a longer time than normal soils. Electrical conductivity in these soils varies from 0.50 to 55.0 dS m^{-1} and pH from 8.5 to 9.0. It has been observed that on both the north and south sides of Rajasthan Canal Feeder (Badopal, Dabli, Seelwala and Tibi areas), the depth of water table is <2 m. Between Rawatsar and Masitawali head, the problem is mainly due to seepage of canal water, whereas in Lunkaransar lift canal area, the problem is of perched water table. Similarly, in part of Ghaggar floodplain area, the problem has developed due to water stagnation in the depressions. Groundwater is saline in large part of IGNP with EC varying between 0.4 and 39.6 dS m^{-1}. However, presence of a cushion of good-quality water in the Ghaggar plain and low EC (3.0 dS m^{-1}) in the vicinity of canals, indicating fresh water quality zone is developing gradually and floating over the poor-quality groundwater, and has tremendous scope for irrigation. Since there is no natural drainage system, more and more areas are getting waterlogged and salinized resulting in desertification. A sizable area has already gone out of cultivation, and several villages have been abandoned. In some of the extreme cases, people feel that they were better when the irrigation was not introduced in the desert area (Singh 2009).

1.5 Saline Aquaculture-induced Soil and Water Degradation in Coastal Belt

Owing to high remuneration from aquaculture, many rice fields are being converted to brackish water aqua farms during last decade in coastal areas of Andhra Pradesh. Within 10 km of the seacoast, farmers draw and store millions of gallons of salt-laden brackish (35–40 dS m^{-1}) seawater into big aquaculture (prawns) tanks and blended with canal or groundwater to lower salinity to 18–20 dS m^{-1} on nearly 2 lakh ha land of Andhra Pradesh. Due to fatal viral contamination of the prawn ponds, when farmers revert back to rice cultivation, they are unable to grow a successful crop because of severe salinity in the pond soils.

1.6 ICAR Research on Reclamation

In the past, research was conducted by individual scientist or group of scientists of the state departments of agriculture and irrigation, state agriculture colleges and universities and the Imperial Agricultural Research Institute without much technical or material support from the central government. To overcome the food shortages in the country, India embarked on a 5-year development plan, with strong emphasis on agricultural development. The Indian Council of Agricultural Research (ICAR) financed agriculture research schemes to the state departments of agriculture and a country-wide research network with good research infrastructure, and trained man-power was added with the establishment of state agricultural universities during the period of third plan and later. During this period the ICAR started All India Coordinated Research Projects (AICRP), with centres in different state agricultural universities (SAUs) and even in private institutions and colleges located in different agroecological zones of the country. Thus, research on the reclamation of salt-affected soils was mainly carried out under the auspices of the ICAR through:

1. ICAR-sponsored research schemes during the second 5-year plan and ad hoc research schemes
2. All India Coordinated Research Project on Water Management and Soil Salinity (now All India Coordinated Research Project for Management of Salt-affected Soils and Use of Saline Water in Agriculture)
3. The Central Soil Salinity Research Institute, Karnal, set up in 1969

Besides the ICAR projects, alkali soil reclamation research was also carried out by the National Botanical Research Institute, Lucknow, at its farm at Banthra, by individual scientists and postgraduate students in state agricultural universities, traditional universities, research institutes and the state department of agriculture. During the second 5-year plan, the ICAR research projects on land reclamation were located at Ludhiana and Allahabad. The Ludhiana centre carried out research on comparative performance of different chemical amendments like gypsum, press-mud, commercial acids, aluminium sulphate and ferrous sulphate and organic amendments like molasses, farm manure, different kinds of plant residues and *Sesbania* green manure, different crop rotations, deep tillage and nutrient use at Kamma and Nilokheri research stations in Ludhiana and Karnal districts, respectively. The research results of Ludhiana centre were later extended to the field through an Operational Research Project situated in district of Kapurthala and through field demonstrations elsewhere in Punjab. The Allahabad centre conducted research on assessment and use of organic amendments in alkali soil reclamation.

The All India Coordinated Project for Research on Use of Saline Water in Agriculture was first sanctioned during the Fourth Five Year Plan under the aegis of Indian Council of Agricultural Research, New Delhi, at four research centres, namely, Agra, Bapatla, Dharwad and Nagpur. The project undertakes research on saline water use for semiarid areas with light-textured soils, arid areas of black soils region and coastal areas and on the utilization of sewage water, respectively. During the Fifth Five Year Plan, the work of the project continued at the above four centres. In the Sixth Five Year Plan, four centres, namely, Kanpur, Indore, Jobner and Pali, earlier associated with AICRP on Water Management and Soil Salinity were also transferred to this Project, whereas the Nagpur Centre was dissociated. As the mandate of the Kanpur and Indore centres included reclamation and management of heavy-textured alkali soils of alluvial and black soil regions, the Project was redesignated as All India Coordinated Research Project on Management of Salt Affected Soils and Use of Saline Water in Agriculture. Two of its centres located at Dharwad and Jobner were shifted to Gangawati (w.e.f. 1.4.1989) and Bikaner (w.e.f. 1.4.1990), respectively, to conduct research right at the large chunks of salt-affected locations. During the Seventh Plan, the project continued at the above locations. During the Eighth Five Year Plan, two new centres at Hisar and Tiruchirappalli were added. These centres started functioning from 1 January 1995 and 1997, respectively (AICRP 2012–2014). Further, with the addition of four new volunteer centres in 2014, currently this AICRP has the following eight cooperating and four volunteer centres:

Cooperating Centres

- Raja Balwant Singh College, Bichpuri, Agra (Uttar Pradesh)
- Regional Research Station, Acharya N.G. Ranga Agricultural University Bapatla (Andhra Pradesh)
- SK Rajasthan Agricultural University, Bikaner (Rajasthan)
- Agricultural Research Station, University of Agricultural Sciences, Gangawati (Karnataka)
- Department of Soils, CCS Haryana Agricultural University, Hisar (Haryana)
- Agriculture College, RVS Krishi Vishwa Vidyalaya, Indore (Madhya Pradesh)
- Agriculture College, CS Azad University of Agriculture & Technology Kanpur (Uttar Pradesh)
- Agriculture College and Research Institute, Tamil Nadu Agricultural University, Tiruchirappalli (Tamil Nadu)

Volunteer Centres

1. Regional Research Station, Punjab Agricultural University, Bathinda (Punjab)
2. Khar Land Research Station, Panvel (Maharashtra)
3. ICAR-Central Island Agricultural Research Institute, Port Blair (A&N Islands)
4. Rice Research Station, Kerala Agricultural University, Vyttila, Kochi (Kerala)

It is a coincidence that the ICAR-CSSRI is located on the bank of western Jamuna canal along which soil salinity was first reported in 1855 at the village of Munak, about 30 km downstream the bridge near ICAR-CSSRI. The institute focuses the research on the reclamation and sustainable management of salt-affected soils and on the rational use of poor-quality water in agriculture. The institute research programs are implemented through four research divisions: Soil and Crop Management, Crop Improvement, Irrigation and Drainage Engineering and Technology Evaluation and Transfer. Besides the main campus at Zarifa Viran Village, Kachhwa Road, Karnal (Harayana), the institute has three regional research stations at Canning Town (West Bengal), Bharuch (Gujarat) and Lucknow (Uttar Pradesh).

Regional Research Station, Canning Town, West Bengal, was transferred from ICAR-CRRI, Cuttack, to ICAR-CSSRI in 1970. The station conducts research to generate location-specific technologies for the productive use of coastal saline soils. To conduct researches on inland salinity of the black soil (Vertisols) regions of the country, a regional research station was established at Anand in Gujarat in 1989. The research activities were carried out at the research farm in Khanpur. On the recommendations of the QRT (1986–1995), the station was shifted to true Vertisol area in Bharuch in 2002. Third Regional Research Station was established, at Lucknow in Uttar Pradesh in 1999, to deal with the problems of alkali soils of central and eastern parts of Indo-Gangetic Plains having problems like surface drainage congestion, high water table, relatively heavy-textured soils and indurated pan.

ICAR-CSSRI has digitized maps of salt-affected soils on 1:2, 50,000 scales for all 15 states having salt-affected soils. Total salt-affected area in the country has been computed to be 67, 44,968 ha. ICAR-CSSRI has also prepared a first approximation map of groundwater quality on 1:6 million scales. Approximately 32–84% area under arid and semiarid states is covered under saline/sodic groundwater. Chemical amendment (gypsum)-based package of alkali soil reclamation technology for reclamation has been developed, standardized for different types of alkali soils and popularized. It has been handed over to State Land Reclamation Development Corporation for large-scale implementation. Subsurface drainage technology consisting of a network of concrete or PVC pipes covered with gravel or synthetic filter, installed manually or mechanically at design spacing and depth below soil surface, has been developed and standardized for different textural class soils. It has been found very effective in controlling the water table and promoting the salt leaching process. The technology, developed initially for Haryana, has been widely adopted and replicated in Rajasthan, Gujarat, Punjab, Andhra Pradesh, Madhya Pradesh, Maharashtra and Karnataka. As a follow-up of Indo-Dutch project, the institute was associated with Haryana Operational Pilot Project (HOPP), and this collaboration is ongoing for the monitoring of large-scale drainage projects in various districts of the state. The technology in Maharashtra is now being pursued under Public-Private Partnership Limited, Sangli, with funding from the Ministry of Rural Development to the Water Resources Department, Maharashtra (CSSRI – At a glance 2010).

For enhancing crop productivity in salt-affected areas, ICAR-CSSRI has developed eight salt-tolerant varieties of rice (CSR 46 in 2014, CSR 43 in 2011, CSR 36 in 2005, CSR 23 in 2004, CSR 30 in 2001, CSR 13 and CSR 27 in 1998 and CSR 10 in 1989), five salt-tolerant varieties of wheat (KRL 1–4 in 1990, KRL 19 in 2000, KRL 210, KRL 213 in 2010 and KRL 283 in 2018), five salt-tolerant varieties of mustard (CS 52 in 1997, CS 54 in 2005, CS 56 in 2008, CS 58 in 2017 and CS 60 in 2018) and one chickpea variety (Karnal Chana-1) through hybridization breeding approach (ICAR-CSSRI 2018).

ICAR-CSSRI has developed an augur hole technology for raising forest and fruit tree plantation in salt-affected soils for the reclamation of highly deteriorated (mainly community) lands. Several experiments have been conducted at ICAR-CSSRI, Karnal, and elsewhere to study the performance of grasses in association with salt-tolerant trees like *Prosopis juliflora* and *Acacia nilotica* in unified agroforestry systems (Singh et al. 1988; Singh 1995; Dagar et al. 2001; Singh and Dagar 2005). A field study conducted at Gudha Experimental Farm for 6 years indicated that grass *Leptochloa fusca* has the potential to yield about 20 Mg ha^{-1} of green biomass per annum when planted with *Prosopis juliflora* in an alkali soil of pH 10.4. *Leptochloa* grass, identified as a highly sodicity tolerant species, has a special characteristic where it starts disappearing when sodicity level in the soil decreases that allows the regeneration of other moderately salt-tolerant grasses and other annuals. The results of this experiment clearly indicated that sodic soils can be reclaimed by growing *Prosopis juliflora* and *Leptochloa fusca* for 5 years. During this period, the surface soil is reclaimed, and salt-tolerant crops like Egyptian clover (*Trifolium alexandrinum*), oats and Indian clover (*Melilotus* spp.) can be grown without the application of amendments. Likewise, oats, rye grass and Persian clover have also been established as salinity-tolerant fodder crops which can be successfully grown with saline drainage effluents (Yadav et al. 2007). Apart from this ICAR-CSSRI also developed some important technologies of practical importance, i.e. land-shaping technologies, biodrainage, safer disposal of wastewater in high-rate transpiration of *Eucalyptus* plantations (Minhas et al. 2015) and CSR-BIO consortia for enhancing productivity in sodic soils. Recently, the reclamation work carried out in Indian subcontinent has been documented widely in many quality publications (Dagar et al. 2001; Qadir and Oster 2002; Singh and Dagar 2005; Dagar 2014; Dagar and Minhas 2016; Dagar et al. 2016a, b).

Important Institutions Pursuing Reclamation and Management of Salt-affected Soils

- Water and Land Management Institute (WALMI), Anand, Gujarat
- Command Area Development Authority, IGNP, Rajasthan
- Command Area Development Authority, Tungabhadra Project, Karnataka

- Haryana Land Reclamation & Development Corporation (HLRDC), Haryana
- Uttar Pradesh Bhumi Sudhar Nigam (UPBSN), Lucknow
- Punjab Land Reclamation Development Corporation (PLRDC), Chandigarh
- Gujarat Land Reclamation & Development Corporation, Gandhinagar
- National Bank for Agriculture and Rural Development (NABARD) financing land reclamation and soil improvement projects
- Sundarban Development Board (SDB), West Bengal

1.7 Saline and Sodic (Alkali) Waters for Irrigation

1.7.1 Historical Perspectives and Distribution

Through the ages, man inhabited water scarcity regions. In due course, ecological pressures caused by increase in human and animal population forced him to look for irrigation water resources to grow food and fodder crops. With no choice of different-quality waters, particularly in dry ecologies, he often had to use poor-quality groundwaters, available in the terrain, for irrigation. The instinct of survival in harsh environment has made the man to learn the practices for judicious use of this water to avoid the decline in soil fertility due to saline irrigation. For instance, in western Rajasthan, where saline irrigation has been practised since ages, the farmers chose to raise barley or later a high salt-tolerant variety of wheat (Kharchia), and the land was kept fallow during monsoon to leach down the salt developed due to saline irrigation. Thus, farmers learnt the art of saline irrigation and lived along with salinity from time immemorial.

The International Groundwater Resources Centre (IGRAC) has compiled global geographical distribution of saline groundwater to a depth of 500 m. The total area, where groundwater salinity at shallow or intermediate depth is considered, approximates 24 million km^2, which is about 16% of the total land area on earth (van Weert et al. 2009). Globally, 36 groundwater regions have been identified, and Groundwater Region 25 (basins of West and Central Asia) is the largest area with high groundwater salinity contributing 14% to the total saline groundwater area. The Global Groundwater regions 7 (lowlands of South America), 11 (lowlands of Europe), 24 (mountain belt of central and eastern Asia) and 35 (Eastern Australia) contribute individually to about 6–7% of the total saline groundwater area (Table 1.10). Based on this study, though it is not possible to estimate the volume of saline groundwater, as per population data of year 2000, about 1.1 billion people live in areas with groundwater salinity at shallow and intermediate depths.

1.7.2 Genesis of Saline Groundwater

A large part of saline groundwater often comparable to good-quality water is young and tends to be actively recharged. It is more or less in stagnant condition at greater depths and may have been there already for many thousands or even millions of

Table 1.10 Global distribution of saline groundwater in different areas at shallow and intermediate depths

Global groundwater region	Countries included	Main physiographic units/ geological provinces
1: Western mountain belt of North and Central America	Parts of Canada, USA, Mexico, Guatemala, Belize, Honduras, Nicaragua and Costa Rica, all of El Salvador and Panama	(a) Alaska, (b) Cordilleran Orogen of Canada, (c) Pacific Mountain System, (d) Columbia Plateau, (e) Basin and Range, (f) Colorado Plateau, (g) Rocky Mountains System, (h) Central American ranges (including Mexican Sierras)
2: Central plains of North and Central America	Parts of Canada, USA, and Mexico	(a) Interior platform of Canada, (b) interior plains of USA, (c) interior highlands, (d) Sierra Madre Oriental
3: Canadian shield	Greenland, parts of Canada and USA	(a) Seven geological provinces of Canadian shield, (b) Innuitian orogeny, (c) Hudson Bay Lowlands (d) Arctic Platform, (e) St. Lawrence Platform, (f) Laurentian Platform of the USA, (g) Greenland
4: Appalachian highlands	Part of Canada and USA	(a) Appalachian Orogen in Canada, (b) Appalachian Highlands in the USA
5: Caribbean islands and coastal plains of North and Central America	Cuba, Jamaica, Haiti, Dominican Republic, Puerto Rico and Lesser Antilles; parts of the USA, Mexico, Guatemala, Belize, Honduras, Nicaragua and Costa Rica	(a) Atlantic Planes (incl. Florida Peninsula), (b) Mexican Gulf Plains (incl. Yucatan Peninsula), (c) Caribbean Plains, (d) Caribbean islands
6: Andean belt	Almost the total territory of Chile and parts of Venezuela, Colombia, Ecuador, Peru, Bolivia and Argentina	(a) Andes, (b) Altiplano, (c) Coastal
7: Lowlands of South America	Parts of Venezuela, Colombia, Brazil, Ecuador, Peru, Bolivia, Paraguay, Argentina, Uruguay and Chile	(a) Orinoco basin (Northern llanos Basins), (b) Amazon basin, (c) Pantanal and Gran Chaco, (d) Pampas with Rio de la Plata estuary, (e) Parana Basin, (f) Patagonia plains
8: Guyana Shield	Guyana, Suriname, French Guyana and parts of Venezuela, Colombia and Brazil	(a) Guyana Shield province: mainly Precambrian igneous and metamorphic rocks with low potential for storing and transmitting groundwater. (b) Guyana Coastal province: deltaic multilayer sandy aquifer systems in the coastal lowlands. They are the main aquifers of the region

(continued)

Table 1.10 (continued)

Global groundwater region	Countries included	Main physiographic units/ geological provinces
9: Brazilian Shield and associated basins	Parts of Brazil and Bolivia	(a) Brazilian Shield (North, Central, East and South), (b) Parnaiba Basin, (c) Sao Francisco Basin, (d) Brazilian coastal
10: Baltic and Celtic shield	Iceland, Norway, Sweden, Finland, Ireland and parts of the UK (N. Ireland, Scotland, Wales), France (Bretagne), Estonia (North) and Russia (Karelia)	(a) Baltic Shield
		(b) Norwegian Caledonides, (c) Island of Iceland, (d) Ireland-Scotland Platform, (e) Armorican Massif
11: Lowlands of Europe	Denmark, the Netherlands, Belgium, Luxembourg, Lithuania, Latvia, Belarus, Moldova and parts of the UK (England), France, Germany, Poland, Estonia, Russian Federation, Ukraine, Romania, Bulgaria, Kazakhstan and Turkmenistan	(a) Anglo and Paris Basin, (b) Aquitaine Basin, (c) London and Brabant Platform, (d) Dutch Basin, (e) Northwest German Basin, (f) German-Polish Basin, (g) Russian Platform, (h) Ural Mountains
12: Mountains of Central and Southern Europe	Czech Republic, Slovakia, Switzerland, Austria, Hungary, Portugal, Spain, Andorra, Monaco, Italy, San Marino, Malta, Slovenia, Croatia, Bosnia and Herzegovina, Serbia and Montenegro, Albania, Macedonia, Greece, Cyprus and parts of France, Germany, Poland, Ukraine, Romania and Bulgaria	(a) Iberian Massifs (a.o. the Hesperian Massif) and adjusted coastal plains; (b) Tajo-Duero Basin; (c) Pyrenees; (d) Massif Central; (e) Jura, Vosges and Ardennes; (f) Southern German Basins; (g) Alps; (h) Po Basin; (i) Apennines; (j) Bohemian Massifs; (k) Pannonian Basin; (l) Carpathian Mountains; (m) Dinaric Alps
13: Atlas Mountains	Parts of Morocco, Algeria, Tunisia	(a) Northern Atlas mountain range (Anti, High, Middle and Tell Atlas), (b) El-Shatout depression, (c) Saharan Atlas mountains in the South
14: Saharan basins	Morocco, Algeria, Tunisia, Libya, Egypt, Sudan, Western Sahara, Mauritania, Gambia, Guinea, Senegal, Mali, Niger, Chad	(a) Tindouf Basin, (b) Grand Erg/ Ahnet Basin, (c) Trias/Ghadames Basin, (d) Hamra Basin, (e) Sirte Basin, (f) Erdis/Kufra Basin (Nubian Sandstone), (g) Dakhla Basin (Nubian Sandstone), (h) Nile Valley and Delta, (i) Senegal-Mauritanian Basin, (j) Regubiat High, (k) Taoudeni Basin, (l) Hoggar High, (m) Iullemmeden Basin, (n) Chad Basin, (o) Tibesti (Quadai) Mountains, (p) Ennedi-Darfour

(continued)

Table 1.10 (continued)

Global groundwater region	Countries included	Main physiographic units/ geological provinces
		Uplift, (q) Sudan interior basins (Nubian Sandstone)
15: West African basements	Mauritania, Mali, Guinea, Sierra Leone, Liberia, Burkina Faso, Ghana, Togo, Benin, Nigeria, Cameroon, Central African Republic, Equatorial Guinea, Gabon, Republic of Congo, Democratic Republic of Congo, Angola, Namibia, South Africa	(a) Eburneen Massif, (b) Volta Basin, (c) Niger Delta, (d) Nigerian Massif, (e) West Congo Precambrian Belt, (f) Damer Bel
16: Sub-Saharan basins	Republic of Congo, Democratic Republic of Congo, Angola, Zambia, Zimbabwe, Botswana, South Africa, Mozambique	(a) Congo Basin, (b) Kalahari-Etosha Basin, (c) Kalahari Precambrian Belt (Western part), (d) Karoo Basin, (e) Cape Fold Belt, (f) coastal basins of Mozambique
17: East African basement and Madagascar	Sudan, Democratic Republic of Congo, Uganda, Kenya, Tanzania, Zambia, Mozambique, Zimbabwe, Madagascar	(a) East Congo Precambrian Belt, (b) Luffilian Arch (Katanga system), (c) East Kalahari Precambrian Belt, (d) East Africa Basement (including rifted zones), (e) Tanzania coastal basin, (f) Sediments of Madagascar, (g) Basement of Madagascar
18: Volcanics of East Africa	Ethiopia, Kenya	(a) Amhara Plateau, (b) Eastern Branch of East African Rift Valley
19: Horn of Africa basins	Ethiopia, Somalia, Kenya	(a) Ogaden Basin, (b) Somali Coastal Basin
20: West Siberian platform	Russia	(a) Yenisey Basin, (b) West Siberian Basin, (c) Turgay Depression (basin)
21: Central Siberian Plateau	Russia	(a) Tunguska Basin, (b) Cis-Sayan Basin, (c) Lena-Vilyuy Basin, (d) Anabar-Olenek High, (e) Nepa-Botuoaba Arch, (f) Aldan uplift
22: East Siberian highlands	Russia	(a) Verkhoiansk Range, (b) Cherskii Range, (c) Kolyma Plain, (d) Yukagir Plateau, (e) Anadyr Range
23: Northwestern Pacific margin	Japan, Taiwan, Philippines and parts of Russia	(a) Kamchatka Peninsula, (b) Kuril Islands, (c) Japan, (d) Philippines
24: Mountain belt of Central and Eastern Asia	Parts of Russia, Kazakhstan, Mongolia and China and the	(a) The Altay-Sayan Folded Region (Central Siberia-Mongolia Border), (b) Mongol-

(continued)

Table 1.10 (continued)

Global groundwater region	Countries included	Main physiographic units/ geological provinces
	countries North Korea and South Korea	Okhotsk Folded Region, (c) Baikal-Paton Folded Region (surroundings of Lake Baikal), (d) Aldan Shield in Eastern Siberia, (e) Yinshah Da and Xia Hinggannling Uplift (Yablonovy and Khingan ranges), (f) Sikhote-Alin Folded Region (South-East Siberia), (g) Korean Peninsula
25: Basins of West and Central Asia	Turkmenistan, Uzbekistan, Kazakhstan, Kyrgyzstan, Tajikistan, parts of the countries China, Afghanistan, Iran (North), and Mongolia (South)	(a) Central Kazakhstan Folded Region, (b) Syr Darya Basin, (c) Tian Shan Fold Belt
		(d) Junggar Basin, (e) Tarim Basin, (f) Altushan Fold Belt, (g) Jinguan Minle Wuwei Basin, (h) Erdos Basin, (i) Shauxi Plateau, (j) Taihangshan Yanshan Fold Belt
26: Mountain belt of West Asia	Turkey, Iran, parts of Georgia, Armenia, Azerbaijan, parts of Iraq, Turkmenistan, Afghanistan and Pakistan	(a) Taurus Mountains, (b) Anatolian Plateau, (c) Caucasus, (d) Central Iranian Basins, (e) Elburz Mountains, (f) Zagros Fold Belt and Trust zone (Zagros Mountains)
27: Himalayas and associated highlands	Parts of the countries Afghanistan, Pakistan, Tajikistan, India, Nepal, China, Burma, Thailand	(a) Hindu Kush, (b) Pamir High, (c) Tibetan Plateau, (d) Himalayas, (e) Shan Plateau, (f) Tenasserim Mountains
28: Plains of Eastern China	Eastern China	(a) Manchurian Plain, (b) North China Plain, (c) middle and lower Chang Jiang (Yangtze) River Basin
29: Indo-Gangetic-Brahmaputra plain	Parts of the countries India, Pakistan, Nepal (terai) and Bangladesh and Myanmar	(a) Indus Basin, (b) Ganges Basin, (c) Brahmaputra Basin d) Irrawaddy Basin
30: Nubian and Arabian shields	Saudi Arabia, Egypt, Sudan, Ethiopia, Yemen	(a) Red Sea coastal plains (e.g. Tihama Plains), (b) North Western Escarpment Mountains (Midian and Hiraz), (c) Asir Mountains, (d) Arabian Shield (e.g. Najd Plateau), (e) Yemen Highlands
31: Levant and Arabian platform	Parts of Turkey, Syria, Lebanon, Palestine, Israel, part of Egypt, Jordan, Saudi Arabia, Iraq, part of Iran, Kuwait, Bahrain, Qatar,	(a) Sinai, (b) Euphrates-Tigris Basin, (c) Al Hasa Plain in Saudi Arabia), (d) Central arch with Tuwaig Mountains, (e) Rub-al-Khali Basin, (f) Marib and

(continued)

Table 1.10 (continued)

Global groundwater region	Countries included	Main physiographic units/ geological provinces
	United Arab Emirates, Oman, part of Yemen	Shabwa basins in Yemen, (g) Masila-Jeza Basin (with Wadi Hadramawt), (h) Mountains and plains of Oman
32: Peninsular India and Sri Lanka	Part of India, Sri Lanka	(a) Precambrian basement areas in southern and eastern India, (b) Precambrian basement area of Aravalli Range in Rajasthan, (c) Precambrian basement and sediments of Sri Lanka, (d) Deccan Trap, (e) coastal sedimentary areas
33: Peninsulas and Islands of South-East Asia	China, Vietnam, Laos, Cambodia, Thailand, Malaysia, Indonesia, Brunei, Papua New Guinea	(a) South China Fold Belt, (b) Truong Son Fold Belt, (c) Thailand Basin, (d) Khorat Platform, (e) Tonle Sap-Phnom Penh Basin, (f) Malay Peninsula, (g) Sumatra/Java Magmatic Belt, (h) Sumatra Basin, (i) Sunda Platform, (j) Barito-Kutei Basin, (k) Sulawesi Magmatic Arc
		(l) Irian Basins, (m) New Guinea Mobile Belt
34: Western Australia	Australia	(a) Pilbara Block, (b) Yilgarn Basement Block, (c) Carnarvon Basin, (d) Canning Basin, (e) Officer Basins, (f) Eucla Basin, (g) Kimberly Basement Block, (h) Musgrave Basement Block, (i) McArthur Basin, (j) Wiso and Georgina Basins
35: Eastern Australia	Australia	(a) Gawler Ranges, (b) Great Artesian Basin, (c) Murray Basin, (d) Great Dividing Range, (e) Australian Alps, (f) Tasmania Island
36: Islands of the Pacific	New Zealand, New Caledonia (France), Solomon Islands, Federated States of Micronesia, Vanuatu, Tuvalu, Kiribati, Fiji, Tonga, Samoa, French Polynesia, Marshall Islands (USA), Northern Marianas (USA), Hawaiian Islands (USA)	(a) Bismarck-New Hebrides Volcanic Arcs, (b) Fiji Island, (c) orogenic belt of New Caledonia, (d) Axial tectonic belt of New Zealand, (e) sedimentary basins of New Zealand, (f) Pacific islands West of the American continents

Source: Modified from van Weert et al. (2009)

years. Continuous dissolution over geological times of the reservoirs containing this groundwater may have enriched the mineral contents in the groundwater. This is the reason that the groundwater salinity tends to increase with increasing depth. Genetically, the most saline groundwater bodies are either of the categories, viz. marine, terrestrial (natural), terrestrial (anthropogenic) and mixed origin (Table 1.11), as explained in detail by van Weert et al. (2009).

1.7.3 Classification and Quality Guidelines

About 97% of the total global water is brackish, while the only remaining 3% being fresh in nature. While the world's oceans are unbounded, fresh water available to mankind is virtually the most finite. To meet the food and other requirements for the ever-increasing population, irrigation 'the most important sector' uses >70% of the global fresh water withdrawals and 90% of the total consumptive uses. At global level out of the total irrigated area of ~310 million ha (Mha), 117 Mha (38%) are irrigated with groundwater (FAO 2012).

Beneath many of the world's deserts (Thar Desert of the Indian subcontinent, Arab Desert of the Middle East countries, Sahara Desert in North Africa, Kalahari Desert in Southern Africa, Atacama Desert in South America, California Desert in North America, West Australian Desert) are reserves of saline water. The information for saline water use on the global prospective is reported from about 50 countries, which are using saline water for irrigation in one or other forms. These countries are virtually from the semiarid and arid regions, except some developed nations, which make use of the wastewater for irrigation. To meet the demands of the ever-increasing population, the use of saline water in agriculture is inevitable. Therefore, we need extra research efforts in saline agriculture for the judicious use of saline and other poor-quality waters.

Usually, in practice, water often is classified into a number of discrete salinity classes. Number and names of classes, parameters to which class limits are linked (total dissolved solids (TDS) and chloride content, EC) and numerical values of class limits vary among published classifications. Freeze and Cherry (1979), based on TDS levels, classified the waters (Table 1.12).

The salinity levels are specified in terms of chloride content (mg Cl L^{-1}) or EC (μS cm^{-1} or dS m^{-1}). Approximate conversions to TDS (mg L^{-1}) from μS cm^{-1} can be made by using the respective multipliers of 1.8 and vice versa by 0.7. In this inventory the lower limit of 1000 mg L^{-1} TDS is used. Thus, when talking in this report about saline groundwater, this tacitly includes brackish groundwater and brines as well.

For assessing the quality of irrigation water, main parameters determined are salt content (EC, dS m^{-1}), sodium adsorption ratio [SAR $= Na^{+}/\sqrt{}(Ca^{2+} + Mg^{2+})$, mol L^{-1}], residual alkalinity [RSC $= (CO_3^{2-} + HCO_3^{-}) - (Ca^{2+} + Mg^{2+})$ meq L^{-1}], divalent cation ratio (DCR $= \sum M^{2+}/\sum M^{n+}$) and presence of specific ions such as NO_3, F, B and Se. Based on the characteristic features of majority of groundwater in use with the farmers in different agroecological regions and the above indices,

Table 1.11 Genetic categories and typical environment at the time of origin of saline groundwater

Main class of origin	Genetic category or salinization mechanism	Typical environment at the time of origin
Marine origin	Connate saline groundwater	Coastal zone (off-shore)
	Intruded by marine transgressions	Coastal zone (off-shore)
	Intruded by recent incidental flooding by the sea	Coastal zone (onshore)
	Laterally intruded seawater	Coastal zone (onshore)
	Intruded seawater sprays (aerosols)	Coastal zone (onshore)
	Mixture of marine and recent incidental flooding by sea	Coastal zone (on- and off-shore)
	Mixture of connate water marine transgression and recent incidental flooding by sea	Coastal zone (on- and off-shore)
Terrestrial origin (natural)	Produced by evaporation (concentration)	Shallow water table zones in arid climate
	Produced by dissolution of subsurface salts	Zone of salt tectonics or regional halite or other dissolvable formations
	Produced by salt-filtering membrane effects	At depth in thick sedimentary basins containing semipermeable layers
	Emanated juvenile water and other products of igneous activity	Regions of igneous activity
	Mixture of evaporation and dissolution	Shallow water table zones in arid climates and aquifers containing dissolvable formations
Terrestrial origin (anthropogenic)	Produced by irrigation (input of concentrated residual water)	Arid and semiarid zones; shallow depths
	Anthropogenically polluted groundwater	Anywhere on earth, particularly in modern consumptive societies
Mixed origin	Saline groundwater produced by mixing of above three classes mineralized groundwater with fresh water or with another type of saline groundwater	Anywhere on earth; hydraulic gradients facilitate the mixing processes

Source: van Weert et al. (2009)

Table 1.12 Water salinity classification based on TDS levels

Class	Class limits (TDS range, in mg L^{-1})
Fresh water	0–1000
Brackish water	1000–10,000
Saline water	10,000–100,000
Brine	>100,000

After Freeze and Cherry (1979)

Table 1.13 Classification of saline water

Water class	EC (dS m^{-1})	Salt concentration (mg L^{-1})	Type of water
Nonsaline	<0.7	<500	Drinking and irrigation
Slightly saline	0.7–2	500–1500	Irrigation
Moderately saline	2–10	1500–7000	Primary drainage water and groundwater
Highly saline	10–25	7000–15,000	Secondary drainage water and groundwater
Very highly saline	25–45	15,000–35,000	Very saline groundwater
Brine	>45	>35,000	Seawater

Source: Rhoades et al. (1992)

irrigation waters have been broadly grouped (Minhas and Gupta 1992) into good water (ECiw <2 and SAR<10), saline water (ECiw>2 and SAR<10), high SAR saline water (ECiw>4 and SAR>10) and alkali waters (ECiw variable, SAR variable and RSC>2.5). Rhoades et al. (1992) classified saline waters (Table 1.13) in terms of salt concentration, which is the major quality factor generally limiting the use of saline water for crop production.

Ragab (1998) critically examined the possibilities and constraints in the use of brackish water for irrigation and merits of sprinkler and drip irrigations for the saline water use. Kandiah (1998) derived strategies to minimize adverse environmental impacts of the saline water use in agriculture. The guidelines recommended for productive use of saline irrigation water (Minhas and Gupta 1992; Rhoades et al. 1992) are given in Table 1.14.

1.7.4 Utilization for Irrigation

In India, the use of poor-quality waters in irrigation is not new. Agriculturists, particularly in dry ecologies learnt to use these waters judiciously with care so that there is no harm to their land due to use of these waters. JW Leather reported as early as 1895 about use of poor-quality waters in his survey report (Leather 1895) and mentioned the existence of two wells in Petlad area of Gujarat just 65 m apart, one with a highly saline water and the other with good-quality water termed “sweet water” by the farmers. Farmers used the first only in the cold season and at the time of planting the crop and water of second only if the monsoon failed. They might have found that saline irrigation would be less detrimental in the cold season. They have been irrigating crops like tobacco with highly saline groundwaters when these contained substantial quantities of nitrates. In many dry regions, in the event of failure of monsoon rains or low rainfall, the cropping was done in alternate years or, in extreme cases, only in 3 years to provide for adequate salt leaching from surface soil depths (Singh 1998b). Thus, farmers had understanding of leaching down the salts developed due to saline irrigation, during rainy season. Gupta and

Table 1.14 Guidelines for saline irrigation waters (RSC <2.5 me L^{-1}) in India

Soil texture (% clay)	Crop tolerance	Upper limits of ECiw (dS m^{-1}) in rainfall (mm) region		
		<350 mm	350–550 mm	550–750 mm
Fine soil (>30%)	Sensitive	1.0	1.0	1.5
	Semi-tolerant	1.5	2.0	3.0
	Tolerant	2.0	3.0	4.5
Moderately fine soil (20–30%)	Sensitive	1.5	2.0	2.5
	Semi-tolerant	2.0	3.0	4.5
	Tolerant	4.0	6.0	8.0
Moderately coarse soil (10–20%)	Sensitive	2.0	2.5	3.0
	Semi-tolerant	4.0	6.0	8.0
	Tolerant	6.0	8.0	10.0
Coarse soil (<10%)	Sensitive	–	3.0	3.0
	Semi-tolerant	6.0	7.5	9.0
	Tolerant	8.0	10.0	12.5

Source: Minhas and Gupta (1992)

Abhichandani (1970) observed that 350 to 450 mm annual rainfall adequately desalinized the surface 40 cm soil depth of sandy loam to sandy clay loam soils in western Rajasthan, where farmers used highly saline irrigation waters in wheat-fallow rotation. With experience, the farmers also learnt to rotate irrigation where alternative source of water was available. Dagar et al. (2008) cultivated a cafeteria of crops in isolation and in agroforestry mode in dry areas of Hisar (annual rainfall ~500 mm) in sandy loam soils irrigating with water of EC 8–12 dS m^{-1} and found that if there was normal rainfall of the area during 1 year in 3–4 years (which always is there), there was no significant development of soil salinity in the soil profile, and one could get normal crops all through these years.

The experiences of saline irrigation have not always been happy. Jain and Saxena (1970) found accumulation of sodium and boron in the soils irrigated for 20 years with brackish groundwaters in Udaipur and Chitor districts of Rajasthan where annual rainfall is about 600 mm. In fact, saline waters are largely responsible for the widespread incidences of salinity in well-irrigated soils in Rajasthan. However, the experiences gained from the farmers' fields have helped in organizing meaningful researches on saline irrigation and in preparation of general guidelines for irrigation with waters of wide ranges of quality, soil, crop and climatic variations under average levels of management (Bajwa et al. 1975; Manchanda 1976, 1998; Ayers and Westcot 1989; Manchanda et al. 1989; Gupta 1990; Minhas and Gupta 1992; Rhoades et al. 1992; Yadav et al. 2003, 2007; Dagar and Minhas 2016). The saline water irrigation program also includes the irrigation with the drainage effluent water and the wastewater, which have been alternatively developed in many countries (Minhas et al. 2015; Yadav and Dagar 2016). Many of these studies have been basic in nature to understand ion-chemistry, specific ion toxicities, relationship with climate and salinity tolerance by different crops, while others have helped in solving the problems directly in field such as irrigation management (leaching requirement, frequency of irrigation, conjunctive use of available poor-quality water with good-quality water, fertilizer management and use of amendments such as gypsum in beds of high RAC waters. Some reports indicate that salt tolerance in plants could be increased by sowing their seeds pre-soaked in salt solution and also in some cases treating seeds with some growth hormones. Thus, many of these studies have demonstrated that waters of much higher salinities and sodicities than those customarily classified unsuitable for irrigation are being used effectively for the production of selected crops under suitable conditions. In the light of such experiences, it is, therefore, imperative to identify and give due consideration to causes and factors that make the utilization of saline groundwater an effective preposition in irrigated agriculture.

Boyko (1966) was among the pioneers to draw attention to the possibility of crop production using seawater for irrigation. Mass (1985, 1990) produced the exhaustive research data for the limits of salt tolerance in field crops, grasses and fruit crops. Based on this work, Tanwar (2003) compiled the consolidated information on salt tolerance and yield potential of selected crops as influenced by irrigation water salinity, while in India very useful information was generated on salinity limits of irrigation water for different arable crops (AICRP CSSRI, 2000–2009) particularly for arid and semiarid regions. In recent years, however, several researchers have promoted the use of halophytes and demonstrated their economic potential to produce a large and diverse number of traditional and new products using saline water including drainage and wastewaters, seawater for irrigation and marginal land resources (Dagar 2018). Recently, many salt-tolerant crops of high economic value such as medicinal and aromatic crops, and fruit-based agroforestry systems could be promoted with saline irrigation and found highly remunerative and promising, particularly in dry ecologies (Dagar 2003, 2014, 2018; Tomar et al. 2010; Dagar and Minhas 2016; Dagar et al. 2008, 2013, 2015). Many species have been domesticated for saline agriculture, and couples of chapters have been included in this volume also.

1.8 Conclusions

Existence of salt-affected soils and groundwater salinity is a widespread problem in the world. Salt problem can cause decrease in agricultural yields and profits, destroy fertile agricultural lands, cause health problems, jeopardize livelihoods, increase costs of infrastructure maintenance and costs of industrial processes and ultimately change or destroy ecosystems. All these usually depend on how much judiciously and with what procedure we use these marginal resources. With ever-increasing population and wider dependence on good-quality water for drinking, irrigation and developmental activities makes the use of poor-quality water inevitable in irrigation. Present knowledge about the use of salt-affected soils and saline water in agriculture gives a broad overview of possible technical, scientific, managerial and institutional measures that are undertaken worldwide to mitigate or adapt to their judicious and sustainable use in agriculture. To be able to manage saline soil and groundwater;

researchers, water resources specialists, policymakers and politicians need information on the scope, distribution, dynamics and severity of soil and groundwater salinity. The information given in this chapter and the entire book will contribute to provide such essential information for different stakeholders including researchers, policymakers and broader group of people to rehabilitate salt degraded resources, i.e. salinized soil and water for livelihood security of people.

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2 A Brief Review on Soil Salinity Mapping by Optical and Radar Remote Sensing

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Abstract
This paper summarized the recent progress in soil salinity detection, prediction, quantification, and mapping by remote sensing technology. The following aspects such as classification-based mapping technique, biophysical indicators and spectral indices application, potential of radar data, and machine learning regression were all reviewed.

Keywords and Abbreviations

ANN	Artificial neural networks
ARVI	Atmospherically resistant vegetation index
CNN	Convolutional neural networks
DEM	Digital elevation model
EVI	Enhanced vegetation index
GDVI	Generalized difference vegetation index
IBL	Instance-based learning
LST	Land surface temperature
ML	Maximum likelihood
MLR	Multivariate linear regression
NDVI	Normalized difference vegetation index
NDII	Normalized difference infrared index
NIR	Near infrared
OSAVI	Optimized soil-adjusted vegetation index
PCA	Principal components analysis

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PLSR	Partial least square regression
R	Red
RF	Random forests
RFR	Random forest regression
SAR	Synthetic-aperture radar
SARVI	Soil-adjusted and atmospherically resistant vegetation index
SAVI	Soil-adjusted vegetation index
SI	Salinity index
SVM	Support vector machines
SVR	Support vector regression
SWIR	Shortwave infrared
VNIR	Visible and near infrared

2.1 Introduction

Soil salinization is a common environmental hazard in irrigated lands worldwide, especially, in dry areas (Metternicht and Zinck 2003; Farifteh et al. 2006), for example, in Central and Western Asia (Qadir et al. 2008, 2009; Wu et al. 2014a, b, 2018; Ivushkin et al. 2017). On average, 20% of the world's irrigated lands are affected by salinity, and this number increases to more than 30% in Iran and Egypt (Metternicht and Zinck 2003), 50–51% in Uzbekistan (Qadir et al. 2009; Ivushkin et al. 2017), and 60% in Mesopotamia, Iraq (Buringh 1960; Wu et al. 2014a). Soil salinity has greatly influenced crop production. The mechanism behind is that the soluble salts concentrated in the topsoil and subsoil interfere with the growth of most crop plants as a result of increase in soil osmotic pressure. As far as Mesopotamia in Iraq is concerned, crop production has declined by 30–60% in salt-affected area in comparison with the non-affected croplands (Wu et al. 2014a, 2018). Therefore, it is a pressing issue to investigate the severity and distribution of soil salinity in space and time to support decision-makers in planning agricultural development to mitigate food insecurity in the salt-affected countries.

Traditionally, soil salinity assessment and mapping are conducted by soil surveys and interpolation of analytical results of soil samples. Nevertheless, such conventional means of soil survey needs a great deal of time (Ghabour and Daels 1993) and funding investment (Wu et al. 2014b) and can be focused only in a small area. Such situation did not change until the appearance of peaceful application of remote sensing technology in the 1970s. The latter has provided a possibility and opportunity for mapping and assessing soil salinity more efficiently and economically from local scale to regional scale (Garcia et al. 2005; Wu et al. 2014a, b). Mougenot et al. (1993), Metternicht and Zinck (2003), Allbed and Kumar (2013), and Gorji et al. (2015) have, respectively, conducted a review on remote sensing of soil salinity. However, with the development of new approaches and algorithms, it is necessary to update the new progress made and the state of the art of the remote sensing application in salinity assessment for audience. This paper is aimed at achieving such a review work.

As Mougenot et al. (1993) and Rao et al. (1995) have noted, the main factors affecting the reflectance are quantity and mineralogy of salts, soil moisture, color, and surface roughness, and even sun elevation angle. Often, salts are concentrated in the subsoils in which the salinity is difficult to be detected by optical remote sensing (Farifteh et al. 2006; Wu et al. 2014b). However, this can be overcome by geophysical measurement using EM38 (an electromagnetic instrument made by Geonics Ltd) and radar remote sensing (Wu et al. 2014a, b, 2018, 2019) since both can penetrate to subsoil up to a depth of 0.5–1.5 m. Thence, this review will be focused on the new progress by taking all these factors into account.

2.2 Classification-based Mapping

One of the most conventional applications of remote sensing is to map soil salinity through classification approaches. In fact, Dale et al. (1986), Singh and Dvivedi (1989), and Goossens and van Ranst (1998) conducted image classification to delineate salt-affected soils and gypsiferous soils. Dwivedi and Rao (1992) and Verma et al. (1994) proposed best band combination (e.g., Landsat TM bands 135) or optimal band combination (e.g., TM234 plus thermal band) for mapping salt-affected soils. Rodriguez et al. (2007) introduced PCA and NDVI for this purpose, whereas Furby et al. (2010) did this by using TM data together with DEM and its derivatives. They concluded that integration of DEM data could improve classification accuracy.

Different from the above authors, Eldeiry and Garcia (2010) tested the best Landsat TM band combination including NDVI for different kriging techniques to interpolate unsampled pixels while mapping soil salinity at different croplands. Their results showed that R, NIR bands, and NDVI are the best band combination for alfalfa, and NIR, TIR and NDVI for corn, and B together with TIR for wheat. Among the observed kriging approaches, namely, the ordinary kriging (OK), regression kriging (RK), and cokriging (CK), OK model performed the best. Douaoui et al. (2006) obtained the similar result; OK outperformed the other regression and classification method. Bannari et al. (2018) suggested to use SWIR bands 1 and 2 of Sentinel-2 MSI (Multispectral Instrument) and Landsat 8 OLI (Operational Land Imager) data to discriminate and model soil salinity as they are better correlated with the measured salinity than other VNIR bands.

Apart from the conventional classifiers such as ML (Wu and Zhang 2003; Wu et al. 2016), Eklund et al. (1998) used several machine learning classifiers, namely, decision-tree-based C4.5 (an inductive learning), IBL (based on the nearest neighbor), multi-pass instance learning (MPIL), and backpropagation (neural networks) to map second soil salinization by employing Landsat TM, geomorphic, geological, and groundwater data. They found that the decision-tree-based C4.5 algorithm outperformed the others. Cai et al. (2010) utilized SVM (Vapnik and Lerner 1963; Vapnik et al. 1997) to classify salt-affected soils based on the texture features. Wu and Zhang (2003) and Wu et al. (2016) employed the conventional and machine learning classifiers such as ML, ANN, SVM, and RF (Breiman 2001) to conduct accurate land cover mapping including extraction of saline or salinized areas. In their research, besides the uncorrelated TM bands 147 (Wu and Zhang 2003), GDVI (Wu 2014), LST, landscape features derived from DEM, and phenologically contrasted characters of the vegetation cover were also taken into account. A very high mapping accuracy of 95–96% was reported.

A new trend arising in image classification is deep learning (Dechter 1986; LeCun et al. 2015) represented by the CNN algorithm (Matusugu et al. 2003; Ciresan et al. 2011; Krizhevsky et al. 2012; LeCun et al. 2015). It was reported that CNN can achieve accurate classification; hence, it can be a potential application for soil salinity mapping in future as a supplementary classifier to SVM and RF.

2.3 Spectral Indices and Biophysical Indicators for Salinity Detection and Mapping

In the past decades, while effort was made to illustrate the spectral response of the salt-affected soils (Mougenot et al. 1993; Rao et al. 1995), a number of authors (Major et al. 1990; Steven et al. 1992; Brunner et al. 2007; Lobell et al. 2010; Wu et al. 2014a, b; Mokarram et al. 2015; Zhang et al. 2015; Rahmati and Hamzehpour 2017; Paliwal et al. 2018; Wu et al. 2018, 2019) have applied different vegetation indices (VIs) for soil salinity detection and mapping. These VIs are, namely, NDVI, SAVI (Huete 1988), ARVI (Kaufman and Tanré 1992), SARVI (Kaufman and Tanré 1992), OSAVI (Rondeaux et al. 1996), EVI (Huete et al. 1997; Huete et al. 2002), GDVI (Wu 2014), etc.

At the same time, other researchers have proposed some specific salinity indices for the same purpose, and here are the examples. Hardisky et al. (1983) and Steven et al. (1992) used NDVI, NDII (TM4 and 5), and ND23 (normalized difference between TM2 and 3) to analyze canopy stress caused by salinity or by chlorosis and found that NDII (TM4 and 5) performed best. Khan et al. (2001), Al-Khaier (2003), Khan et al. (2005), Douaoui et al. (2006), Iqbal (2011) and Elhag (2016), etc. have proposed several salinity indices (SI), while Fernández-Buces et al. (2006) developed a combined spectral response index (COSRI) based on NDVI. These indices are presented in Table 2.1.

In case of the Tuz Lake in Turkey, Gorji et al. (2015) concluded that SI1 showed the best correlation with the measured salinity followed by SI2. Elhag (2016) found that SI8 performed best than another SI and followed by SI4 and BI in Wadi Al Dawasir, Saudi Arabia. But as we can see in Tables 2.2 and 2.3, the so-called salinity indices performed differently in the two sites in central Iraq, e.g., SI1, SI4, and SI8 were meaningful in the Dujaila site, whereas they seemed nothing in the Mussiab site. BI and NDSI did not show any good relationship with salinity. On the contrary, NDII45 of Hardisky et al. (1983) or its inversed version of Al-Khaier (2003) and COSRI seemed to be stable salinity indicators among the salinity indices.

Based on hyperspectral data, Zhang et al. (2011) proposed a number of soil-adjusted salinity indices (SASI) which perform better than NDVI and SAVI. When using hyperspectral data, these SASIs may be applied for salinity assessment.

Table 2.1 Vegetation and salinity indices (SI)

Index Name	Formula	Sources
SI1	$SI1 = (B*R)^{1/2}$	Khan et al. (2001) and Khan et al. (2005)
SI2	$SI2 = (G*R)^{1/2}$	Khan et al. (2005)
SI3	$SI3 = (R*NIR)^{1/2}$	This study
SI4	$SI4 = [(G)^2 + (R)^2 + (NIR)^2]^{1/2}$	Douaoui et al. (2006)
SI5	$SI5 = [(G)^2 + (R)^2]^{1/2}$	Douaoui et al. (2006)
SI6	SI6 = (SWIR1-SWIR2)/(SWIR1 + SWIR2)	Al-Khaier (2003)
SI7	SI7 = (SWIR1-NIR)/(SWIR1 + NIR)	Al-Khaier (2003)
SI8	SI8 = (NIR*R)/G	Elhag (2016)
Brightness index (BI)	$BI = [(R)^2 + (NIR)^2]^{1/2}$	Khan et al. (2001) and Khan et al. (2005)
NDII	(NIR-SWIR1)/(NIR + SWIR1)	Hardisky et al. (1983) and Steven et al. (1992)
ND23	(G-R)/(G + R)	Steven et al. (1992)
ND47	(NIR-SWIR2)/(NIR + SWIR2)	Steven et al. (1992)
Normalized difference salinity index (NDSI)	NDSI = (TIR - NIR)/(TIR + NIR) (in digital number)	Iqbal (2011)
Combined spectral response index (COSRI)	COSRI = [(B + G)/(R + NIR)] *NDVI	Fernández-Buces et al. (2006)

Note: Band named in terms of Landsat TM, e.g., *B* blue, *G* green, *R* red, *NIR* near infrared, *SWIR1* ($\lambda = 1.65$ μm) shortwave infrared band 5, *SWIR2* ($\lambda = 2.16$ μm) shortwave infrared band 7, and *TIR* thermal infrared

In summary, for broadband satellite data, VIs such as SAVI, EVI, ARVI, and SARVI are also well correlated with salinity. However, GDVIs have performed best (Wu et al. 2014a, b, 2019). The recommended VIs and SIs for salinity detection and mapping would be hence LST, GDVI2, GDVI3, NDVI, NDII45, and COSRI, which were stably important carriers of salinity information among all the test sites.

2.4 Applicability of Radar Data

An interesting attempt has been made on the application of radar data for salinity mapping in the past decades. Singh and Srivastav (1990), Singh et al. (1990), Sreenivas et al. (1995), Taylor et al. (1996), Shao et al. (2003), Aly et al. (2004), Lasne et al. (2008), and Gong et al. (2013) have argued the potential to employ the microwave C-, P-, and, especially, L-bands for detecting salinity in different settings. Shao et al. (2003) and Gong et al. (2013) found that soil salinity has a significant contribution to the backscattering coefficient of RADARSAT SAR images, because the signal can penetrate through the surface and reach subsoil at a depth of >1.5–2.0 m, depending on the soil characters and moisture. The independence from atmospheric conditions offers radar an advantage over the optical and infrared

Table 2.2 Pearson correlation coefficients of the spectral indices with the measured apparent soil salinity (ECa) at the Dujaila site, Iraq

ECa	LST	SI1	SI2	SI3	SI4	SI8	NDII45	NDII57	BI	NDSI	NDVI	GDVI2	GDVI3	COSRI
EM_V	0.564	0.504	−0.266	0.343	−0.479	−0.549	−0.612	−0.553	0.111	0.382	−0.621	−0.621	−0.617	−0.617
EM_H	0.560	0.476	−0.305	0.320	−0.490	−0.544	−0.601	−0.539	0.094	0.340	−0.602	−0.602	−0.599	−0.594

Note: EM_V and EM_H are, respectively, the vertical and horizontal EM38 readings. EM_V can penetrate the topsoil and reach the subsoil at a depth of 1.5 m, while EM_H can reach only a depth of 0.5 m. NDSI is the reflectance-based difference between the thermal and near infrared bands, different from the digital number (DN)-based NDSI of Iqbal (2011)

Table 2.3 Pearson correlation of the spectral indices with the measured apparent soil salinity (ECa) at the Mussaib site, Iraq

ECa	LST	SI1	SI2	SI3	SI4	SI8	NDII45	NDII57	BI	NDSI	NDVI	GDVI2	GDVI3	COSRI
EM_V	0.722	0.047	0.273	−0.087	0.152	0.055	−0.474	−0.232	−0.169	0.028	−0.414	−0.465	−0.470	−0.452
EM_H	0.728	−0.101	0.228	−0.247	0.128	0.049	−0.414	−0.209	−0.320	0.020	−0.397	−0.437	−0.464	−0.429

satellite-borne sensors. While the real part is independent of soil salinity and alkalinity, the imaginary part is highly sensitive to both variations in soil electrical conductivity and moisture. This allows the separation of saline soils from the others. However, as Mougenot et al. (1993) were concerned about, the disadvantage of radar application is that the characterization of saline soils using complex dielectric constants determined by radar backscattering inversion techniques requires some soil moisture data. Probably due to the difficulty to separate or retrieve the salinity from the soil moisture, successful radar-based salinity detection and mapping studies have been rarely reported. A breakthrough has not been made until very recently in the works of Wu et al. (2018, 2019).

Employing ALOS L-band radar data, Wu et al. (2018, 2019) used Landsat TM images, which were acquired at the same time as the radar images, to correct or minimize the impacts of vegetation cover on the backscattering coefficients based on the water cloud model proposed by Attema and Ulaby (1978). In this minimization procedure, it was required to obtain the vegetation canopy descriptors V_1 and V_2, which were represented, respectively, by Leaf Area Index (LAI) and vegetation water content (VWC) according to Kumar et al. (2012). They used LAI-GDVI model of Wu (2014) to provide LAI (V_1) and VWC-NDVI model of Jackson et al. (2004) to calculate VWC (V_2). Regarding the vegetation parameters, A and B, the second case for L-band radar data of Dabrowska-Zielinska et al. (2007) were selected for minimization processing after many tests (Wu et al. 2019). After such removal or correction of vegetation cover, the retrieved backscattering coefficients of soil were highly correlated to the measured soil salinity ($R^2 = 0.565–0.677$). This correction improved the correlation coefficients between the radar backscattering coefficients of soil and the measured soil salinity, respectively, by 16.6–25.6% for HH and 11.5–21.4% for HV polarization bands. Radar-based soil salinity maps with an accuracy of 70–79% were produced. Please refer to Wu et al. (2018, 2019) for detail.

Therefore, EM38 readings (geophysical measurement) and L-band radar data would be an ideal combination for salinity detection since both of them can reveal the salinity up to subsoils, overcoming the shortcoming of optical data. In addition, the works of Wu et al. (2018, 2019) also demonstrated that it seemed more practical to remove or minimize the vegetation cover impacts from the total backscattering coefficients rather than to separate the salinity from the moisture in the imaginary part of the radar data.

2.5 Machine Learning Regression

Though machine learning classifiers such as ANN, SVM, RF, and C4.5 have been applied to soil salinity mapping as mentioned above, a potential momentum will be gained by machine learning regression algorithms. Farifteh et al. (2007) have applied PLSR and ANN, and Taghizadeh-Mehrjardi et al. (2014) used regression tree, and

Wu et al. (2018) employed SVR and RFR for salinity prediction and mapping. Comparing the most frequently applied and promising machine learning algorithms, Wilkinson (2005), Mas and Flores (2008), and Wu et al. (2016) found that ANN was often outperformed by other algorithms such as SVM and RF and even by ML. PLSR was tested in the Mussaib site in central Iraq, but the prediction accuracy was not ideal, much lower than RFR and SVR (Wu et al. 2018). Thus, both PLSR and ANN would not be recommended for soil salinity prediction. Regression tree is a part of RF and RFR; the latter would be hence more robust (Breiman 2001). Another disadvantage in the work of Taghizadeh-Mehrjardi et al. (2014) is that they treated the measured apparent soil salinity by EM38 instrument as one of the independent variables but not as ground-truth data for training or validation. The majority of pixels of the apparent soil salinity layer was interpolated from the EM38 readings, and the validity of such interpolated data as input for modeling is doubtful.

In view of these, Wu et al. (2018) employed the most hotspotted regression algorithms SVR and RFR for soil salinity prediction using a combined Landsat TM and L-band radar dataset. The abovementioned minimization of vegetation cover impact was conducted to retrieve the backscattering coefficients of soil. Field measured apparent soil salinity (mS/m) was regarded as training set (TS) for modeling. They found that both RFR and SVR algorithms could achieve relevant salinity prediction but RFR performed better than SVR with higher accuracy (93.4–94.2% vs 85.2–89.4%) and less normalized root mean square error (NRMSE) (6.10–7.69% vs 10.29–10.52%) when calibrated with both TS and validation set (VS). Also, they noted that MLR could produce good salinity maps with less NRMSE than SVR using the same optical-radar combined dataset. Another advantage of MLR lies in its capacity to deliver intuitive models that can be applied elsewhere. Hence, they recommended to use RFR and MLR for soil salinity quantification and mapping.

2.6 Summary

As the state of the art of soil salinity detection and mapping by remote sensing technology, the algorithm of CNN shall be adapted or developed for classification-based mapping. The so-called salinity indices are sensitive to locality and lack stability for widespread application, and it would be better to use LST and vegetation indices such as GDVI, NDVI, SAVI, EVI, ARVI, COSRI, etc., for this purpose. Radar data have really great potential, but combined optical-radar datasets may allow to derive better prediction and mapping with higher accuracy. Machine learning regression, especially, RFR is recommended for accurate soil salinity mapping.

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Synergy Between Sentinel-MSI and Landsat-OLI to Support High Temporal Frequency for Soil Salinity Monitoring in an Arid Landscape

3

A. Bannari

Abstract

The free-available data acquired with multispectral instruments (MSI) onboard Sentinel-2 satellites and Operational Land Imager (OLI) installed on Landsat 8 satellite significantly advances the virtual constellation paradigm for Earth observing and monitoring with medium spatial resolutions ensuring a revisiting interval time less than 5 days. Although these instruments are designed to be similar, they have different spectral response functions and different spectral and spatial resolutions, and, therefore, their data probably cannot be reliably used together. In this chapter, we analyzed exclusively the impact of dissimilarities caused by spectral response functions between these two sensors for high temporal frequency for soil salinity dynamic monitoring in an arid landscape. Knowing that the *shortwave infrared* (SWIR) spectral bands are the most appropriate for soil salinity discrimination, modeling, and monitoring, only the land surface reflectances in the SWIR spectral bands are considered and converted to the *Soil Salinity and Sodicity Index* (SSSI) and to the *semiempirical predictive model* (SEPM) for soil salinity mapping. These three products were compared, and the impact of the sensors' (OLI and MSI) spectral response function differences was quantified. To achieve these, analysis was performed on two pairs of images acquired in July 2015 and August 2017 with 1-day difference between each other over the same study area, which is characterized by several soil salinity classes (i.e., extreme, very high, high, moderate, low, and nonsaline). These images were not cloudy, without shadow, and not contaminated by cirrus. They were radiometrically and atmospherically corrected, and bi-directional reflectance difference factors (BRDF) were normalized. To generate data for analysis, similarly to Landsat-OLI, Sentinel-MSI images were resampled in 30 m pixel size considering UTM projection and WGS84 datum. The comparisons of the derived products

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were undertaken using regression analysis ($p \leq 0.05$) and root mean square difference (RMSD). In addition to the visual analysis, kappa coefficient was also used to measure the degree of similarity between the derived salinity maps using SEPM. The results obtained demonstrate that the two used pair's dataset, acquired during 2 different years over a wide range of soil salinity degrees ($2.6 \leq \text{EC-}_{\text{Lab}} \leq 600$ dS m^{-1}), had very significant fits (R^2 of 0.99 for the SWIR land surface reflectances and $R^2 \geq 0.95$ for SSSI and SEPM). Moreover, excellent agreement was observed between the two sensor products, yielding RMSD values less than 0.012 (reflectance units) for the SWIR bands and less than 0.006 for SSSI. For the SEPM, the calculated RMSD vary between 0.12 and 2.65 dS m^{-1}, respectively, for nonsaline and extreme salinity classes, reflecting relative errors varying between 0.046 and 0.005 for the considered soil salinity classes. Statistical similarity between the derived salinity maps based on SEPM using kappa coefficient revealed an excellent agreement (0.94). Therefore, MSI and OLI sensors can be used jointly to characterize and to monitor accurately the soil salinity and its dynamic in time and space in arid landscape, provided that rigorous preprocessing issues (sensor calibration, atmospheric corrections, and BRDF normalization) must be addressed before.

Keywords

Sentinel-MSI · Landsat-OLI · Shortwave infrared · Soil salinity · Soil salinity index · Semiempirical predictive model · Arid landscapes

3.1 Introduction

Food security and safety, water security, biodiversity protection, human heath, terrestrial ecosystem services, sustainability, etc. are all depending on the soil security, which is a biophysical, scientific, economic, and societal concept (McBratney et al. 2014). Unfortunately, soil salinity threatens seriously this security. Nowadays, soil salinity or salinization is the consequence of a combination of several factors such as the irrigation water quality and management practices, the crop type, the soil quality and permeability conditions, the fertilization rate, the water table depth, groundwater quality, the poor drainage conditions, and micro-topography. Moreover, the climate change impact is another important and severe phenomenon affecting and catalyzing the soil salinization during this last half of the century. Indeed, it becomes an undeniable reality with a broad consensus of the international scientific community on the significance of its impacts directly or indirectly on soil salinity and, consequently, on the soil biodiversity and related ecosystems (Mandal and Neenu 2012; Teh and Koh 2016; Dagar et al. 2016). It is known that global warming increases temperature, reduces soil moisture regime and crop duration, increases crop evapotranspiration, affects the survival and distribution of soil microorganisms, decreases fertilizer use efficiency, and, subsequently, increases soil salinity and land degradation (Shahid and Behnassi 2014; Castro et al. 2010; Jucevica and Melecis 2006; Dagar et al. 2016).

Soil salinity phenomenon is not new on Earth surface, and it was known since the Sumerian time in the Mesopotamian plains 5000 years ago (Santis 1996). It exists around the world in different environments and different climates; however, flat and low semiarid and arid landscapes are more affected. Indeed, in humid regions, leaching by rainfall tends to remove salts, preventing their accumulation in the upper layers of the soil. While, arid landscapes are seriously facing challenge of spatial and temporal distribution of soil salinity, particularly during drought periods (Dai 2011), due to water quality and scarcity, the high temperature and the increased evapotranspiration rate (Kurylyk and MacQuarrie 2013). In addition to water stress, these landscapes are vulnerable to salinization, marginality, and desertification as consequences of human activities (Shahid and Al-Shankiti 2013) and global climate change impact as mentioned above (Teh and Koh 2016). Obviously, these factors have significant impacts on land degradation, crop production, food security, economic aspects, and infrastructure, as well as ecosystem functionality, human well-being, and sustainable development (Naing et al. 2013). Around the world, especially in semiarid and arid environments (White et al. 2002), soil salinity affects approximately 40–45% of the Earth land, and the global cost of irrigation-induced salinity is estimated around 11 billion US$ a year (FAO 2005). To remedy this situation in vulnerable landscapes to salinization, there are methods available to slow down the processes and, sometimes, even reverse them. However, remedial actions require reliable information to help set priorities and to choose the type of action that is most appropriate for a specific location. In affected areas, farmers, soil managers, scientists, and agricultural engineers need accurate and reliable information on the nature, extent, magnitude, severity, and spatial distribution of the salinity against which they could take appropriate measures (Metternicht and Zinck 2003).

Monitoring soil salinity in space and time is complicated by its dynamic nature and requires repeated measurements. Globally, measuring electrical conductivity extracted from a saturated soil paste at the laboratory ($EC_{\text{-Lab}}$) is the most accurate method used for soil salinity mapping and monitoring (Zhang et al. 2005). Unfortunately, this method requires conventional soil sampling procedures which are expensive and time-consuming, especially for regular monitoring over a long period and for comparisons over large areas (Metternicht and Zinck 1997; Goosens et al. 1998). During the last two decades, remote sensing technology and processing methods have outperformed these conventional methods. Currently, new remote sensing satellite instruments measuring soil salinity, coupled with modeling, programming, and mapping in *geographic information system* (GIS) environment, have significantly improved the potential for soil salinity monitoring in space with a very high temporal frequency (Ben-Dor et al. 2003, 2009; Nawar et al. 2014; Bannari et al. 2016, 2017a, 2018). The main advantage of remote sensing is represented by providing an opportunity for mapping large areas at relatively low cost and collecting information at regular intervals; therefore, monitoring becomes easier. This allows not only for the appropriate remedial action to be taken but also for the monitoring of the effectiveness of any ongoing remediation or preventative measures, which facilitate monitoring, management, and decision-making (Zinck 2000).

Furthermore, actually, the availability of the new generation of medium spatial resolution, such as multispectral instruments (MSI) onboard Sentinel-2 satellites (A and B) and Operational Land Imager (OLI) sensor installed on Landsat 8 platform, offers new opportunities for long-term high temporal frequency for Earth surfaces' observation and monitoring (Mandanici and Bitelli 2016). The free availability of their data significantly advances the virtual constellation paradigm for mid-resolution land imaging (Roy et al. 2014; Wulder et al. 2015a, b; Zhang et al. 2018). Thanks to the improvement of their spectral, radiometric, and temporal resolutions, they can expand the range of their applications to several natural resources and environmental domains for monitoring, assessing, and investigating (Hedley et al. 2012). The orbits of this satellite constellation are designed to ensure a revisiting interval time, less than 5 days (Li and Roy 2017), thereby substantially increasing monitoring capabilities of the Earth's surface and ecosystems (Drusch et al. 2012). Their spectral resolutions and configurations are designed in such a way that there is a significant match between the homologous spectral bands (Drusch et al. 2012; Irons et al. 2012). However, depending on the sensitivity of the intended application (Flood 2017), the sensor radiometric drift calibration (Markham et al. 2014), the atmospheric corrections (Vermote et al. 2016), the surface reflectance anisotropy (Roy et al. 2017), and the sensor co-registration (Skakun et al. 2017; Yan et al. 2018), it is plausible that the natural surface reflectances between MSI and OLI may be different. In addition, the relative spectral response profiles characterizing the filters (spectral responsivities) of these instruments are not identical between the homologous bands, so some differences are probably expected in the recorded land surface reflectance values; therefore, their data cannot be reliably used together (Bannari et al. 2004; Van-derWerff and Van-derMeer 2016). Obviously, the importance of these differences depends on the application (spectral characteristics of the observed target) and on the approach adopted to perform time series analyses, mapping, or change detection exploiting both instruments (Flood 2017). For instance, it is plausible that the extraction of soil salinity information in time over arid landscape using surface reflectances, empirical, semiempirical, and/or physical approaches, can affect the result comparison. This chapter analyzes and compares the difference between land surface reflectances in the *shortwave infrared* (SWIR) homologous spectral bands of MSI and OLI sensors for soil salinity dynamic monitoring in an arid landscape. In addition, comparisons were carried out in terms of transformation of these surface reflectances to the *Soil Salinity and Sodicity Index* (SSSI) and then to the *semiempirical predictive model* (SEPM) for salt-affected soil mapping.

3.2 Material and Methods

Figure 3.1 summarizes the used methodology; it exploits two pairs of images acquired with Sentinel-MSI and Landsat-OLI sensors over the same study site with 1-day difference between each pair. The first pair was acquired on the 29th and 30th of July, 2015, respectively, for OLI and MSI. The second pair was recorded

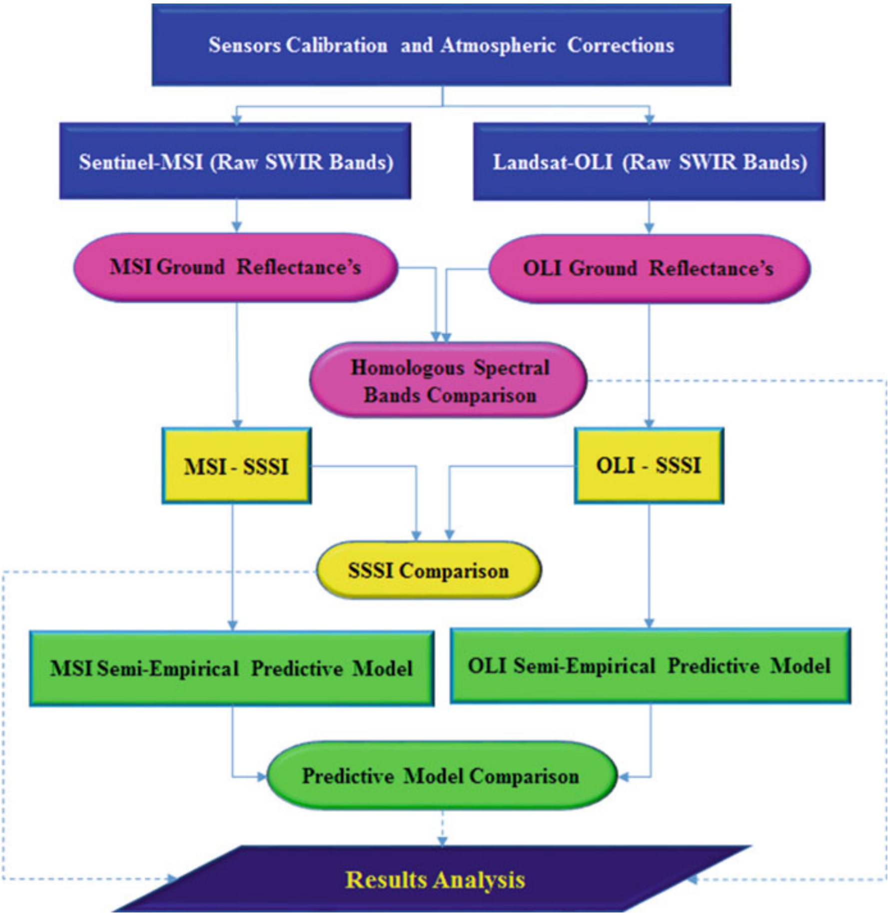

Fig. 3.1 Flowchart of the methodology

the 18th and 19th of August 2017 for MSI and OLI, respectively. These images were not cloudy, not contaminated by cirrus, and without shadow effects because significant topographic variations are absent in the study area. They were radiometrically and atmospherically corrected to transform them to the ground surface reflectances, and the bi-directional reflectance difference factors (BRDF) were normalized to allow their meaningful comparison correctly. Then, the ground reflectances in SWIR bands were converted to SSSI and to SEPM for soil salinity mapping. For comparison and sensor spectral response function difference quantification on these three considered products, statistical fits were conducted using linear regression analysis ($p \leq 0.05$), and the root mean square difference (RMSD) was calculated. In addition to the visual analysis, kappa coefficient was also used to measure the degree of similarity between the derived salinity maps based on SEPM.

3.2.1 Study Site

The Kingdom of Bahrain (25°32′ and 26°00′N, 50°20′ and 50°50′E) is an archipelago of 33 islands located in the Arabian Gulf, east of Saudi Arabia and west of Qatar (Fig. 3.2) with a total land area of about 778.40 km^2. According to the aridity criteria and the great variations in climatic conditions, Bahrain has an arid to extremely arid environment (Elagib and Abdu 1997). The climate is characterized by high summer temperatures of an average 45 °C during June to September and an average of approximately 17 °C in winter from December to March. Rain is sparse and occurs primarily from November to April, with an annual average of 72 mm, sufficient only to support the most drought-resistant desert vegetation. Mean annual relative humidity is over 70% due to the surrounding Arabian Gulf water, and the annual average potential evapotranspiration rate is 2099 mm (FAO 2015). Under such climatic conditions, where precipitation is excessively low to maintain a regular percolation of rainwater through the soil, soluble salts are accumulated in the soil, influencing soil properties and environment causing low soil productivity. Indeed, these factors have significant impacts on land degradation, crop production, and economic aspects of local agriculture (Naing OO et al. 2013). Geologically, Bahrain is characterized by Eocene and Neocene rocks, which are partly covered by Quaternary sediments and a complex of Pleistocene deposits. The dominant rocks are limestone and dolomitic limestone with subsidiary marls and shales. The leading structure is the north–south axis of the main dome, with minor cross-folds predominantly tilting

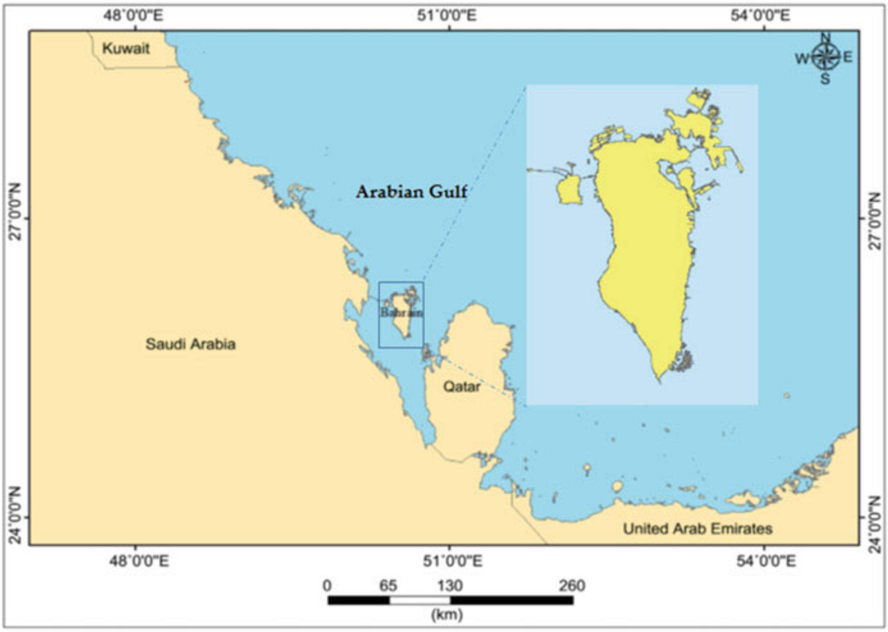

Fig. 3.2 Study site (Kingdom of Bahrain)

from northeast to southwest. The beds are gently inclined toward the coast from the center of the main island. The fringes of Bahrain are covered by more recent marine and Aeolian sand dunes, which were derived from the Arabian land connection across the present Arabian Gulf.

3.2.2 Sentinel-MSI and Landsat-OLI Image Data

The Sentinel-2 mission is the result of close collaboration between the European Space Agency, the European Commission, industry, service providers, and data users. It is composed of two satellites, Sentinel-2A which was launched in June 2015 and Sentinel-2B that was launched in Mars 2017. Both satellites are equipped with identical MSI sensors to provide continuity to the SPOT missions and to improve the Landsat-OLI temporal frequency (Drusch et al. 2012). In fact, the synergy between Sentinel-MSI and Landsat-OLI significantly increases the temporal resolution (less than 5 days) offering new opportunities for several environmental and natural resource applications, such as the vigor of vegetation cover, emergency management, soil salinity dynamics, water quality, and climate change impact analysis at local, regional, and global scales. The MSI images the Earth's surface reflectivity with a large FOV (20.6°) in 13 spectral bands with several spatial resolutions from 10 to 60 m: 4 bands with 10 m (blue, green, red, and NIR-1), 6 bands with 20 m (red edge, NIR-2, and SWIR), and 3 bands with 60 m (coastal, water vapor, and cirrus). The swath of each scene is 290 km, permitting global coverage of the Earth's surface every 10 days. The MSI radiometric performance is coded in 12 bits, enabling the image acquisition in 4095 digital numbers, ensuring radiometric accuracy of less than 3% and an excellent SNR (Markham et al. 2014; Li et al. 2017). The geometric registration precision is better than 0.15 pixels, and it was shown that no visual obvious misregistration was observed when the multi-temporal MSI data were used (Yan et al. 2018). Table 3.1 summarizes the effective bandwidth characteristics of the MSI sensor.

Since 1972, the Landsat scientific collaboration program between the NASA and USGS constitute the continuous record of the Earth's surface reflectivity from space. Indeed, the Landsat satellite series support more than four and a half decades of a global medium spatial resolution data collection, distribution, and archive of the Earth's continental surfaces (Bannari et al. 2004; Loveland and Dwyer 2012; NASA 2015) to support research, applications, and climate change impact analysis at the global, the regional, and the local scales (Roy et al. 2014; Wulder et al. 2015a, b; Roy et al. 2016). On 11 February 2013, the polar-orbiting Landsat 8 satellite was launched, transporting two push-broom instruments: **OLI** and **TIRS**. The OLI sensor collects land surface reflectivity in the visible and near-infrared (VNIR), SWIR, and panchromatic wavelength with a FOV of 15° covering a swath of 185 km with 16 days' time repetition at the equator. The band passes are narrower in order to minimize atmospheric absorption features (NASA 2014), especially the NIR spectral band (0.865 μm). Two new spectral bands have been added: a deep blue visible shorter wavelength (band 1, 0.433–0.453 μm) designed specifically for water

Table 3.1 The Sentinel-MSI and Landsat-OLI effective bandwidths and characteristics (λ = wavelength, SNR = signal to noise ratio)

Spectral bands	Sentinel-MSI					Landsat-OLI				
	λ Center (nm)	Δλ (nm)	Pixel size (m)	SNR	L_{ref} (λ) (w/m^2/Sr/μm)	λ Center (nm)	Δλ (nm)	Pixel size (m)	SNR	E_0(λ) (w/m^2/μm)
Coastal	443	20	60	129	129	443	16	30	130	1895.6
Blue	490	65	10	154	128	482	60	30	130	2004.6
Green	560	35	10	168	128	561	57	30	100	1820.7
Red	655	30	10	142	108	655	38	30	90	1549.4
NIR-2	865	20	20	72	52.5	865	28	30	90	951.2
SWIR-1	1609	85	20	100	4	1609	85	30	100	247.6
SWIR-2	2201	187	20	100	1.5	2201	187	30	100	85.5

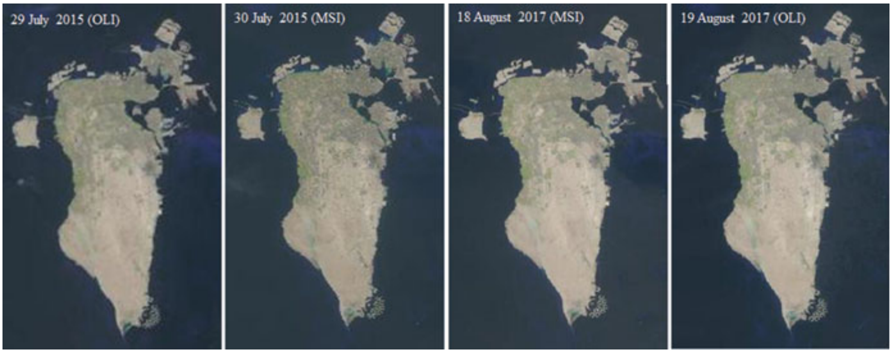

Fig. 3.3 True color composite of raw OLI and MSI image data acquired over the Kingdom of Bahrain in July 2015 (left) and August 2017 (right)

resources and coastal zone investigation and a new SWIR band (9, 1.360–1.390 μm) for the detection of cirrus clouds. Moreover, the OLI design results in a more sensitive instrument with a significant amelioration of the SNR radiometric performance quantized over a 12-bit dynamic range (level 1 data); raw data are delivered in 16 bit. This SNR performance and improved radiometric resolution provide a superior dynamic range and reduce saturation problems associated with globally maximizing the range of land surface spectral radiance and, consequently, enable better characterization of land cover conditions (Knight and Kvaran 2014). According to Gascon et al. (2017) and Markham et al. (2014), Landsat 8-OLI and Sentinel-MSI on orbit reflective wavelength calibration are better than 3%. From co-registration point of view, Stumpf et al. (2018) obtained a co-registration accuracy between images provided by both missions around ±3 m by reference to accurate geodetic ground control points. Table 3.1 summarizes the effective bandwidth characteristics of OLI sensor. In this research, two pairs of image data were used. The first pair was acquired with 1-day difference, the 29th and 30th of July 2015 for OLI and MSI, respectively. The second pair was also recorded with 1-day difference in 18 and 19 August 2017, respectively, for MSI and OLI (Fig. 3.3). This very short time between each pairs (MSI and OLI) data acquisition is so important to minimize the impact of surface and atmospheric changes between these sensor observations, as well as the BRDF effects.

3.2.3 Image Data Preprocessing

Prior to launch, the sensors are subject to rigorous radiometric and spectral characterization and calibration. However, postlaunch absolute calibration is an important step to establish the relationship between at-sensor radiance and the digital number (DN) output for each pixel in the different spectral bands. Sensor radiometric calibration and atmospheric corrections (scattering and absorption) are fundamental preprocessing operations to restore the images radiometric quality (Bannari et al.

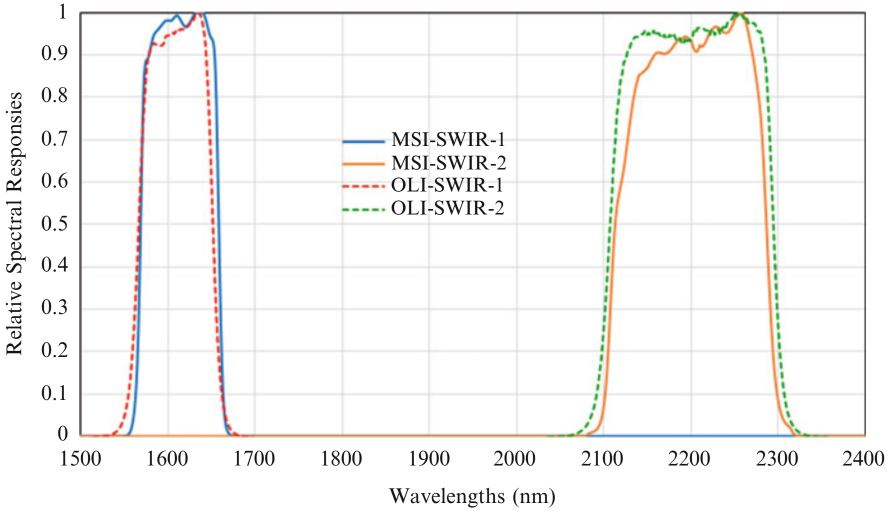

Fig. 3.4 Sentinel-MSI and Landsat-OLI relative spectral response profiles characterizing the filters in the SWIR bands

1999). The changes caused by these artifacts can be mistakenly attributed to changes in the land use and ground biophysiological components, and errors can propagate in all subsequent image processing steps, such as spectral indices calculations, multi-temporal analysis, climate change modeling, etc. (Myneni and Asrar 1994; Pahlevan et al. 2014). For converting the measured DNs by MSI and OLI sensors to the apparent radiance values, the solar zenith angle and rescaling coefficients (gain and offset) delivered by USGS-EROS center were used. Moreover, the *Canadian Modified Simulation of a Satellite Signal in the Solar Spectrum* (CAM5S; Teillet and Santer 1991) based on Herman radiative transfer code (RTC) was used for atmospheric condition simulation to calculate all the requested atmospheric correction parameters in MSI and OLI spectral bands. This RTC simulates the signal measured at the top of the atmosphere (TOA) from the Earth's surface reflecting solar and sky irradiance at sea level while considering the sensors characteristics, such as the band passes of the solar-reflective spectral bands (Fig. 3.4), satellite altitude, atmospheric conditions, atmospheric model, Sun and sensor geometries, and terrain elevation. Consequently, all the requested atmospheric correction parameters were used to transform the apparent reflectance at the TOA to the ground reflectance. Table 3.2 summarizes the input parameters for the CAM5S RTC.

To preserve the radiometric integrity of the images, absolute radiometric calibration and atmospheric effects were combined and corrected in one step (Teillet 1992) to generate ground surface reflectance images using the Canadian image processing system PCI Geomatica (PCI Geomatica 2018). Furthermore, knowing that Earth's natural surfaces do not have a Lambertian spectral behavior, both solar and observing zenith angles exert a radiometric distortion impact on surface reflectances

Table 3.2 Input parameters for the CAM5S RTC (ASL, above sea level; GMT, Greenwich Mean Time; ppm, parts per million)

Parameters	MSI image	OLI image
Terrain elevation (ASL)	0.755 km	
Sensor elevation	786 km	705 km
Date of overflight	30 July 2015	29 July 2015
Time of overflight (GMT)	10:22:47	10:04:19
Solar zenith angle (deg.)	20.201	23.811
Solar azimuth angle (deg.)	106.636	102.523
Date of overflight	18 August 2017	19 August 2017
Time of overflight (GMT)	10:20:33	10:04:46
Solar zenith angle (deg.)	22.516	26.010
Solar azimuth angle (deg.)	120.673	116.252
Atmospheric model	Mid-latitude summer	
Aerosol model	Continental	
Horizontal visibility	50 km	50 km
Ozone content	0.319 cm-atm	
Water vapor	2.93 g cm^{-2}	
CO_2 mixing ratio	357.5 ppm (as per model)	

(BRDF problem). According to Roy et al. (2016) along the Landsat-OLI bands (edges by reference to the image center), the reflectance can vary by less than 6% due to these BRDF effects. Moreover, Roy et al. (2017) reported that this problem can affect the Sentinel-MSI bands by approximately 8% because of its large FOV. Certainly, these differences may constitute a source of errors for biophysical and physiological parameter extraction and for general remote sensing applications because their values as mentioned before are relatively more meaningful than the sensor calibration errors (Markham et al. 2014) and atmospheric corrections (Gascon et al. 2017). To normalize the BRDF influence on the ground surface reflectance images of both sensors (MSI and OLI), a semiempirical approach based on the geometry of acquisition (Qi 1993) was applied in this research.

3.2.4 Image Data Processing

For soil salinity discrimination and mapping, using simulated spectral data and/or satellite images acquired with different sensors (TM, ETM+, OLI, MSI, ALI EO-1, and WorldView-3), several studies revealed that spectral confusion occurs in the VNIR spectral domain between the salt crust and the artifacts of soil optical properties (Ben-Dor 2002; Ben-Dor and Banin 1994; Metternicht and Zinck 1997, 2003, 2009; Verma et al. 1994; Hashem et al. 1997; Bannari et al. 2017a, b, 2018). In these wavelengths, the main factors affecting the salt-affected soil spectral signatures are represented by the salt types, soil mineralogy, level of moisture, organic matter content, soil color and brightness, roughness, and vegetation cover (Bannari et al.

1996). Obviously, these factors influence the signal gathered by the sensor in a specific pixel size causing severe confusion between the salt in the soils and the soil optical properties (Bannari et al. 2018). Statistical fit between MSI and OLI individual spectral bands and EC-$_{\text{Lab}}$ revealed that only the SWIR bands were correlated significantly ($R^2 > 50\%$), while the R^2 between the VNIR bands and EC-$_{\text{Lab}}$ remains less than 9% (Bannari et al. 2018). Indeed, during the last two decades, literature demonstrated that the SWIR spectral bands allow better discrimination among salt-affected soil classes and they were integrated in soil salinity modeling and monitoring at local, regional, and global scales (Goldshleger et al. 2001). Shrestha (2006) concluded that the SWIR bands were the most correlated with soil salinity. Bannari et al. (2008, 2016, 2017a, b, 2018) found that the SWIR bands of ALI, OLI, SMI, and WorldView-3 offer the best potential for soil salinity detection and discrimination. Considering different soil types and geographic locations, Leone et al. (2007), Odeh and Onus (2008), and Zhang et al. (2011) demonstrated that the SWIR bands could be used for soil salinity estimation in agricultural fields better than VNIR spectral domains. Chapman et al. (1989) showed that the SWIR bands of TM provide excellent discrimination of evaporite mineral zones in salt flats. Drake (1995) described the various absorption peaks of the salts found in evaporite minerals in the SWIR wavelengths. The study undertaken by Hawari (2002) showed that the absorption features in SWIR bands are consistent with the detection of the gypsum, halite, calcium carbonate, and sodium bicarbonate. According to Nawar et al. (2015), the SWIR bands of ASTER exhibited the highest contribution for soil salinity discrimination. Moreover, Rahmati and Hamzehpour (2017) indicated that the SWIR bands of the ETM+ sensor increase the accuracy of the soil salinity prediction.

Furthermore, for soil salinity detection and mapping, many soil salinity spectral indices and models have been proposed in the literature (Fernandez-Buces et al. 2006; Zhang et al. 2011; Fan et al. 2015; Alexakis et al. 2016; Scudiero et al. 2016; El-Harti et al. 2016). A comparative study among several semiempirical predictive models based on soil salinity indices, such as Brightness Index (BI), Normalized Difference Salinity Index (NDSI), Salinity Index (SI), Salinity Index ASTER (SI-ASTER), Soil Salinity and Sodicity Index (SSSI), etc., was achieved for accurate soil salinity detection in irrigated agricultural land (slight and moderate salinity classes) in North Africa (Bannari et al. 2016) and in the arid landscape (slight, moderate, strong, very strong, and extreme salinity classes) in the Middle East (El-Battay et al. 2017). These studies showed that the SEPM model based on SSSI provided the best accuracy for salt-affected soil classes' detection and mapping. In this chapter, the SSSI and SEPM were implemented and calculated, and their comparisons were therefore undertaken in the same way as surface reflectance data to quantify the differences between relative spectral response profiles characterizing the filters of homologous bands of MSI and OLI sensors. Their equations are as follows (Bannari et al. 2016, 2017a):

$$EC_{-Predicted} = C^{ste} \cdot \left[4521 \cdot (SSSI)^2 + 125 \cdot (SSSI) + 0.41\right] \tag{3.1}$$

$$SSSI = (\rho_{SWIR-1} \cdot \rho_{SWIR-2} - \rho_{SWIR-2} \cdot \rho_{SWIR-2})/(\rho_{SWIR-1}) \tag{3.2}$$

where:

$EC_{\text{-Predicted}}$: predicted electrical conductivity semiempirical model
$\rho_{\text{SWIR-1}}$: reflectance in MSI and OLI SWIR-1 channel

$\rho_{\text{SWIR-2}}$: reflectance in MSI and OLI SWIR-2 channel

C^{ste}: scaling factor, which theoretically enables an upscaling between the spatial information measured in the field and its homologous information derived from the image (Bannari et al. 2017a)

In the literature, several methods exist to calculate this factor depending on the remote sensing applications (Wu et al. 2014). In this research, a simple upscaling empirical ratio was calculated between the observed and the predicted values considering six sampled points representing the six salinity classes (extreme, very high, high, moderate, low, and nonsaline). Homogeneous and uniform pixel surface representing each class was located using the GPS coordinates; their homologous ground reference values resulting from the laboratory analysis ($EC_{\text{-Lab}}$) were used to calculate an average and global scaling factor for the entire image.

3.2.5 Soil Salinity Class Identification, Selection, and Labeling

The soils of Bahrain are characterized by five different and major classes associated with moderate to shallow depths and are closely related to the terrain geology and geomorphology (Doomkamp et al. 1980). Based on Bahrain soil and soil salinity maps, six salinity classes are considered in this study: extreme, very high, high, moderate, low, and nonsaline. The extreme soil salinity class is characterized by the presence of high contents of soluble salts and the surface salt crust, which is sabkha (C1 in Fig. 3.5). This class is a natural solonchak soil (loamy and sandy, highly gypsiferous) devoid of any vegetation. The very high saline soil class is also a natural solonchak soil often encrusted with an efflorescence of salt crystals and a well-developed platy structure, and it looks like the creation of a new sabkha (C2 in Fig. 3.5). The high salinity soil class is composed of fine, white, sand-sized shell gravel and gravelly sand (C3 in Fig. 3.5); the surface layers are sometimes cemented by salt and without vegetation cover. The moderate soil salinity class is the dominant class in the southern half of Bahrain Island (C4 in Fig. 3.5). It is a regosol soil, calcareous to highly calcareous, with calcium carbonate and dominated by shells and sand. Very sparse and scattered clumps of halophytic plants (salt tolerant) are observed in the areas covered by this class. Furthermore, in the northwest part of Bahrain Island, we find the spatial distribution of miscellaneous soil class, which is a mix composition of silts and fine sands with low salinity. This low salinity class (C5 in Fig. 3.5), with acceptable fertility potential, is equipped with irrigation

Fig. 3.5 Photos showing the six considered soil salinity classes (C1 to C6) in the study site

systems, and it is the only cultivated area in Bahrain (about 8% of the total area of the country). Finally, the nonsaline soil class describes accurately the man-made (artificial) infrastructure, industrial and urban zones, asphalted roads, and imported soil to build artificial islands (C6 in Fig. 3.5).

These six soil classes were visited in the field; their geographic location was automatically labeled and photographed using a 35 mm digital camera equipped with a 28 mm lens (Fig. 3.5). Their UTM coordinates were recorded using accurate GPS survey ($\sigma \leq \pm 30$ cm) connected in real time to a GIS database integrating the used images (MSI and OLI) for accurate spatial location and identification of each salt-affected soil class. Moreover, during the field visits, samples were collected from each soil class of the top layer (0–10 cm deep) considering an area about 50 × 50 cm. Observations and remarks about each sample (color, brightness, texture, etc.) were noted. In the laboratory, these soil samples were air-dried, crushed, and then sieved to obtain fraction less than 2 mm. Standard USDA laboratory methods and procedures (Zhang et al. 2005; USDA 2004) were used to measure the pH, the electrical conductivity ($EC\text{-}_{Lab}$), and the major soluble cations (Na^+, K^+, Ca^{2+}+, and Mg^{2+}) and anions ($CO_3{}^{2-}$, $HCO_3{}^-$, Cl^-, and $SO_4{}^{2-}$) using extraction from a saturated soil paste, and the SAR was also calculated (USDA 2004). These parameters are considered in this study for the only purpose of providing reliable information about the degree of salinity in each considered soil class assisting the results interpretation and comparison and, in addition, to be sure that all existing soil salinity classes in arid landscape are covered and represented in this study. Based on the spatial representativeness of the six major soil classes and their wide range of salinity content degrees as discussed above, approximately 30 pixels per class were carefully selected based on the measured GPS coordinates' location. Finally, for statistical analysis, a total of 180 homologous points (pixels) were selected from the homologous SWIR spectral bands of each pair of images.

3.2.6 Statistical Analyses

As discussed previously, the MSI and OLI relative spectral response profiles characterizing the filters of each spectral band are relatively different (Fig. 3.4). To examine the impact of this difference, statistical analyses were computed using "Statistica" software. The relationships between derived product values (reflectances, SSSI, and SEPM) from MSI against those from OLI were analyzed using a linear regression model ($p \leq 0.05$). As well, the correlation coefficient (R^2) was used to evaluate the strength of this linear relationship. For this process, the homologous variable values derived from MSI and OLI were compared using the 1:1 line. Ideally, these independent variable values should have a correspondence of 1:1. Additionally, the RMSD between these derived variables (reflectances, SSSI, and SEPM) from both sensors (OLI and MSI) were calculated as follows (Willmott 1982; Zhang et al. 2018):

$$\mathrm{RMSD} = \sqrt{\frac{\sum_{i}^{n} \left(v_i^{OLI} - v_i^{MSI}\right)^2}{n}}$$

where v_i is the variable under analysis and i is the number of variable (i = 1 to n). Furthermore, in addition to the visual comparison, remote sensing explores a variety of quantitative procedures and algorithms for spatial pattern comparison and analysis such as kappa coefficient. The latter is the most popular to measure the overall difference or similarity between two maps (Visser and De-Nijs 2006). In this study, this coefficient is considered to measure the global similarity between the derived salinity maps from MSI and OLI data based on SEPM.

3.3 Results Analysis

Table 3.3 summarizes the major exchangeable cations and anions in the considered six soil sample classes (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, and SO_4^{2-}), pH, $EC\text{-}_{Lab}$, and SAR values. They represent the average values of these chemical elements that were calculated from the sampling points representing each soil class separately. These analyses reveal a very high concentration of sodium (Na^{+}), which generally exceeds the sum of calcium (Ca^{2+}) and magnesium (Mg^{2+}), and dominant chloride anion (Cl^{-}) which exceeds sulfates (SO_4^{2-}). Moreover, we see that, globally, the values of $EC\text{-}_{Lab}$, Na^{+}, and SAR increase gradually and very significantly from nonsaline soil to extreme soil salinity (sabkha). The nonsaline and low soil salinity classes (miscellaneous soils), which support the agricultural system in Bahrain, are characterized by low $EC\text{-}_{Lab}$ ($2.6 \leq EC\text{-}_{Lab} \leq 4.4$ dS m^{-1}) and SAR ≤ 10.3 (mmoles $L^{-1})^{0.5}$. The moderate salinity class ($EC\text{-}_{Lab} \geq 7.4$ dS m^{-1} and SAR ≥ 12.7 (mmoles $L^{-1})^{0.5}$) is the dominant soil class in Bahrain, and it is a part of the regosol soil category that allows for the growth of halophytic plants. Contrariwise, the other three soil salinity classes with high, very high, and extreme

Table 3.3 Laboratory determination of pH, EC-$_{\text{Lab}}$, and ion content in the considered soil salinity classes

			Ca^{2+}	K^+	Mg^{2+}	Na^+	Cl^-	SO_4^{2-}	
Salinity class	EC-$_{\text{Lab}}$ (dS m^{-1})	pH	(mg l^{-1})						**SAR (mmoles $L^{-1})^{0.5}$**
Extreme	507.0	7.6	1276	843	672.0	154700	170715	11275	600.0
V. high	170.0	7.2	1878	1454	2874.0	76373	100281	28020	258.9
High	67.0	7.5	1905	651	1581.0	24171	48546	5488	99.2
Moderate	7.4	8.6	531	67	181.0	1324	2480	881	12.7
Low	4.4	8.2	284	44	96.0	782	1329	754	10.3
Nonsaline	2.6	7.9	154	28	58.4	530	886	63	9.2

salinity content show very strong EC-$_{\text{Lab}}$ ($67 \leq$ EC-$_{\text{Lab}}$ ≤ 600 dS m^{-1}) and very high SAR (≥ 99.2 (mmoles L^{-1})$^{0.5}$) values. These three classes describe the natural solonchak soil category. Moreover, the pH values (7.1–8.6) are very informative as regards the preponderance of carbonate and the presence of bicarbonate in the soils and, consequently, contribute significantly to the alkalinity aspect of the soil. Obviously, these analysis results confirm our choice of divers and representative salt-affected soil classes in arid landscape (Fig. 3.5), which are fundamental for this study.

The SWIR spectral bands of MSI have unlike spatial resolutions (20 m) than those of OLI bands (30 m). To handle this spatial difference and to generate data correspondingly to OLI images for analysis, MSI bands were resampled automatically in 30 m pixel size considering UTM projection and WGS84 datum. Then, comparisons of the derived products were undertaken. For the data acquired in August 2017, Fig. 3.6 shows scatter plots between SMI and OLI surface reflectances in SWIR bands over a wide range of soil samples (180 pixels, assuming implicitly that the surface of each selected pixel is homogeneous and representing only soil) with different salinity degrees ($2.6 \leq$ EC-$_{\text{Lab}}$ ≤ 600 dS m^{-1}). These scatter plots reveal a very good linear relationship (R^2 of 0.99) for SWIR-1 and SWIR-2-homologous spectral bands with the slopes and intercepts very near to unit (1.0278 and 1.0469) and zero (0.0112 and 0.0169), respectively. They indicate that MSI reflectances are relatively very similar to those of OLI in these two bands and the majority of points are located around the line 1:1. The RMSD values are insignificant (0.008 reflectance units) between the SWIR homologous bands. Similar results were obtained for the data acquired in July 2015 showing an excellent agreement (R^2 of 0.99) between the two sensors SWIR homologous bands (Table 3.4), yielding RMSD values quite small (0.012 for SWIR-1 and 0.007 for SWIR-2 reflectance units). Globally, for the two considered pair of images, the reflectances in OLI bands are very slightly lower against those in MSI. The reasons behind these small RMSD differences are likely due to the greater view zenith angle range in Sentinel-MSI (±10.3°) compared to Landsat-OLI (±7.5°). In addition, these may also be due to the BRDF normalization with increasing view zenith angle. However, it is important to remember here that although we consider only

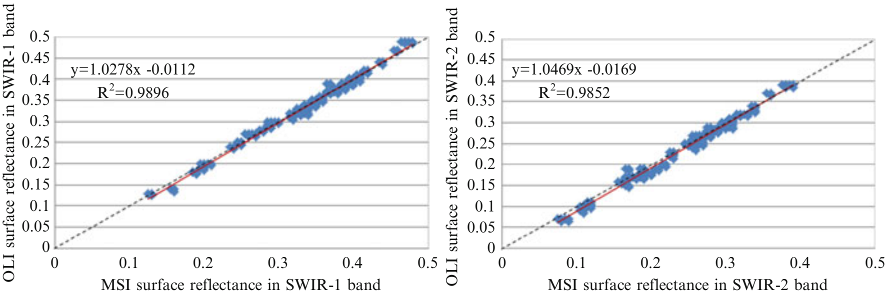

Fig. 3.6 Compared surface reflectances in the SWIR spectral bands acquired with Sentinel-MSI and Landsat-OLI in August 2017

Table 3.4 Linear regression fits ($p \leq 0.05$) between Landsat-OLI and Sentinel-MSI SWIR band reflectances, SSSI, and SEPM and RMSD considering the spectral response function differences

	OLI and MSI acquired in July 2015			OLI and MSI acquired in August 2017		
	Equations	R^2	RMSD	Equations	R^2	RMSD
SWIR-1	OLI = 0.9800 MSI + 0.000	0.99	0.012	OLI = 1.0278 MSI + 0.011	0.99	0.008
SWIR-2	OLI = 1.0000 MSI + 0.000	0.99	0.007	OLI = 1.0469 MSI + 0.017	0.99	0.008
SSSI	OLI = 0.9839 MSI + 0.003	0.97	0.006	OLI = 0.9687 MSI + 0.003	0.95	0.004
SEPM *	OLI = 0.9352 MSI + 0.912	0.96	1.98 *	OLI = 0.9702 MSI + 1.455	0.95	2.65 *

*: dS m^{-1} for electrical conductivity unit; these values are calculated for the extreme salinity class

the sensor spectral response function differences between MSI and OLI sensors, these relatively small differences of RMSD values can also be due to residual errors of atmospheric corrections and sensor radiometric calibration, which are never perfect because they do not apply to the images pixel by pixel but rather band by band (Claverie et al. 2015).

Although this research is focalizing specifically on soil salinity as a specific target, these results obtained are in agreement with previous research projects considering several applications around the world. Indeed, comparing surface reflectances and derived biophysical variables over Australian territory, Flood (2017) showed that SMI and OLI instruments have good compatibility between them with an RMSD less than 0.03 for surface reflectances in VNIR and SWIR bands and around 0.05 for biophysical variables. Considering numerous test sites in Europe, Vuolo et al. (2016) compared surface reflectances and biophysical products of many targets in the homologous bands of MSI and OLI. Their results show that the agreement between the two sensor products is good, yielding RMSD values around 0.03 reflectance units. Some tests performed on simulated data and on the real images data acquired simultaneously with MSI and OLI around the world over a wide variety of land cover types (agricultural fields, inland, and open shallow water) showed a very good correlation (R^2 of 0.98) between homologous bands (Mandanici and Bitelli 2016). Analyzing million pairs of images acquired simultaneously by MSI and OLI sensors over southern African territory with a wide range of natural surfaces and under different surface moisture and atmospheric conditions (winter and summer seasons), Zhang et al. (2018) showed good and significant statistical fits between MSI and OLI apparent reflectances and NDVI ($R^2 > 0.87$), ground surface reflectances and surface NDVI ($R^2 > 0.89$), and ground surface reflectances and surface NDVI corrected from BRDF effects ($R^2 > 0.90$). Moreover, in the laboratory where the atmospheric effects are absent, errors related to radiometric calibration and geometric location are also absent, no topographic variation, no residual clouds or shadows, and no BRDF impact, Zhang et al. (2018) simulated MSI and OLI reflectances using a total of 485 targets spectra (green and dry vegetation, soil, and

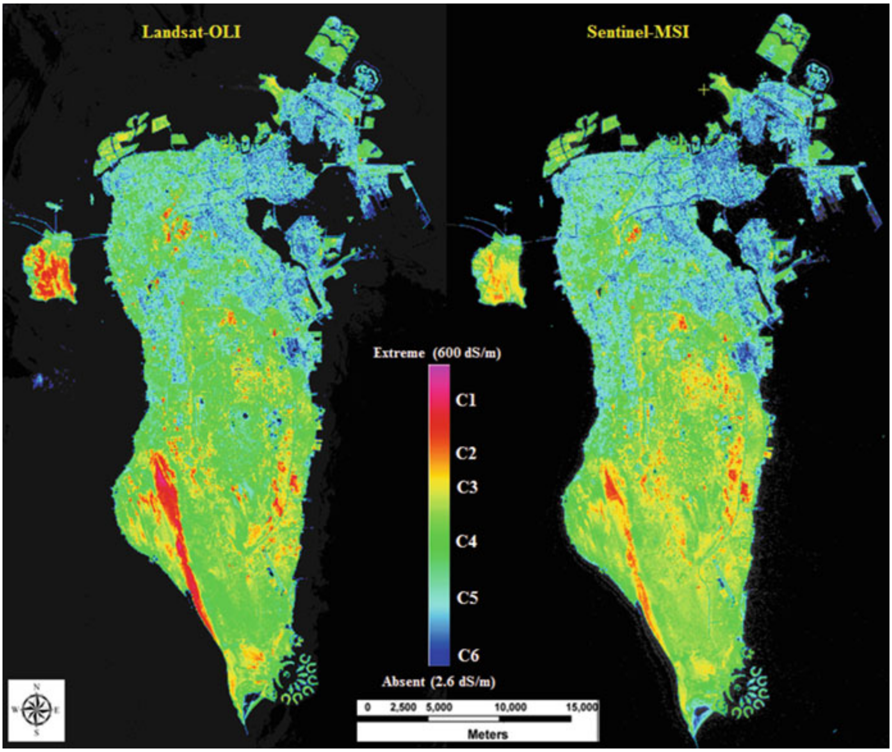

Fig. 3.7 Derived soil salinity maps based on the model SEPM using Sentinel-MSI and Landsat-OLI image data acquired in August 2017

man-made materials). They demonstrated that the impact due only to the spectral response function differences between these two sensors is quite small, with a highly significant fit and RMSD values less than 0.015 for all of the homologous reflective bands, as well as for the NDVI. According to Pastick et al. (2018), observations made by MSI and OLI can be used to monitor accurately land surface vegetation phenology in dry lands of the western United States.

Otherwise, Fig. 3.7 illustrates the soil salinity maps derived from Sentinel-MSI and Landsat-OLI image data acquired in August 2017 using the SEPM. Both maps show an excellent spatial distribution of the six considered soil salinity class patterns in the study site. The extreme salinity class (C1) with pink-red color represents sabkha characterized by the presence of high contents of soluble salts. The very high saline class (C2), presented by the red-orange color, is a natural solonchak soil often encrusted with an efflorescence of salt crystals and a well-developed platy structure (creation of a new sabkha). The yellow color reflects the high soil saline class (C3) composed of fine sand-sized shell gravel and gravelly sand cemented by salt and without vegetation cover. Illustrated by green color, moderate saline class (C4) is dominant, highly calcareous with calcium carbonate and dominated by shells and sand. Scattered clumps of halophytic plants are observed in the areas of this class. The low salinity class (C5) in cyan color is the cultivated areas in Bahrain. Finally, the nonsaline soil class (C6) in blue color describes accurately the man-made (artificial) infrastructure, industrial and urban zones, asphalted roads, and imported soil to build artificial islands. Visual analysis and comparison of these two maps revealed in general a very good similarity between them showing globally the same class patterns. However, despite this similarity, small differences are observed. Firstly, the nonsaline class represented by road networks and urban infrastructure (blue color) is well differentiated in the map of Sentinel-MSI than that of Landsat-OLI. Moreover, the low salinity class (cyan color) representing agricultural fields in the north and northwest of Bahrain Island is relatively underestimated by OLI map and correctly represented in that of MSI. Certainly, regarding these two classes, the recorded small dissimilarities between these maps are not caused by the sensor spectral response function differences concerning the two used sensors. But they are caused by the nominal spatial resolution differences between them. Although the MSI data were resampled from 20 m to 30 m, the integrity of its original spatial resolution (20 m) reflects accurately the internal geometric fidelity of urban structure, road networks, and boundaries of agricultural fields and characterizes the land use classes better than the OLI pixel size (30 m). Indeed, a relative severe cartographic generalization is observed, and it is caused by the mixed details in the 900 m^2 of each OLI pixel. Secondly, the dynamic and the extent of extreme and very high salinity classes are relatively different between these maps. The patterns of extreme salinity class in OLI map are quite less represented on that of MSI. It looks like an overestimation of the extreme salinity class in the OLI map, whereas it is the very high salinity class that seems overestimated in the MSI map. In addition to the unlike spatial resolutions, these relative differences are probably also caused by the signal saturation which is due to the difference in radiometric resolutions between both sensors (i.e., 16 bit $\approx$ 65536 DN for OLI and 12 bit $\approx$ 4096 DN for MSI). This saturation may be more pronounced over bright and strongly reflective surfaces such as white salt crust areas, especially when specular effect is strongly pronounced. It can also be magnified by the BRDF problem (FOV difference). These remarks are also raised up by Mandanici and Bitelli (2016), as well as Knight and Kvaran (2014) who reported that the improved radiometric resolution of OLI provides a superior dynamic range and reduces the signal saturation problems.

Furthermore, despite these small differences visually observed and discussed above, statistical analyses were also achieved. First, the two derived salinity maps (Fig. 3.7) were overlaid on a pixel-by-pixel basis in a GIS environment, and statistical similarity was measured based on kappa coefficient. The results obtained revealed an excellent agreement (0.94) between these two maps. Second, based on GPS location, the generated 180 soil samples (pixels) representing the 6 different salinity classes used above for homologous SWIR bands analysis are also used for statistical fits of derived products (SSSI and SEPM). Figure 3.8 illustrates the scatter plot of SSSI and SEPM derived from Sentinel-MSI and Landsat-OLI data acquired in August 2017.

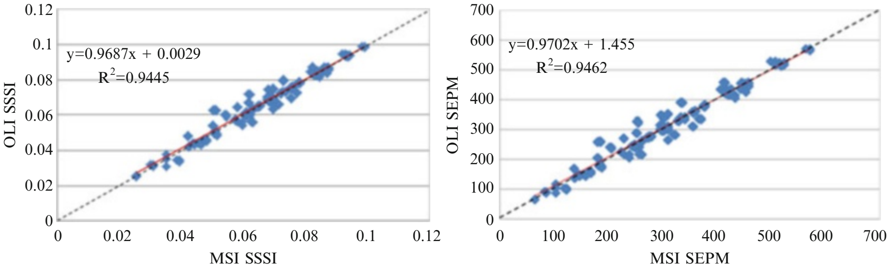

Fig. 3.8 Comparison of SSSI (left) and SEPM (right) derived from Sentinel-MSI and Landsat-OLI images data acquired in August 2017

The SSSI values fit significantly with the line 1:1 (R^2 of 0.945) showing a slope of 0.969, intercept of 0.003, and RMSD of 0.0038 (Fig. 3.8 and Table 3.4). Moreover, the predicted salinity values using the SEPM fit well with 1:1 line expressing an excellent correlation (R^2 of 0.946) between the two sensors, with a slope near to the unit (0.970) and intercept of 1.455. The scatter plot shows also a relative overestimation of very high salinity class ($200 \leq \text{EC-}_{\text{Lab}} \leq 450$ dS m^{-1}) in the OLI map than that of MSI. However, the RMSD calculated for SEPM vary between 0.12 and 2.65 dS m^{-1}, respectively, for nonsaline and extreme salinity classes. These RMSD reflect relative errors varying between 0.046 and 0.005 for the considered soil salinity classes ($2.6 \leq \text{EC-}_{\text{Lab}} \leq 600$ dS m^{-1}). Likewise, for the acquired data during July 2015, the homologous SSSI and SEPM products had also significant fits ($R^2 \geq 0.96$). The achieved RMSD values are 0.006 for SSSI and between 0.155 and 1.98 dS m^{-1} for SEPM for nonsaline and extreme salinity classes, respectively (Table 3.4). These differences reflect relative errors less than around 0.058, which are quite identical to the electrical conductivity accuracy measurements in the filed using electronical instruments (Rhoades et al. 1999).

According to these independent results analysis (regression fits, RMSD, visual, and kappa coefficient), it is observed that the impact of the dissimilarities caused by spectral response functions between the homologous SWIR spectral bands of Sentinel-MSI and Landsat-OLI is quite small, as well as on the derived products (SSSI and SEPM). In general, statistical fits are highly significant ($0.95 \geq R^2$), and the reached RMSD values less than 0.012 remain smaller than the accuracy (0.03) of radiometric calibration process as demonstrated by Markham et al. (2014). Moreover, despite the small differences concerning certain class patterns that are observed between the two soil salinity maps, the kappa coefficient revealed that these maps are not statistically different showing a good degree of similarity (0.94). Consequently, these results point out that these two sensors can be combined for high temporal frequency for soil salinity dynamic monitoring in an arid landscape. However, rigorous preprocessing issues (sensors calibration, atmospheric corrections, and BRDF normalization) must be addressed before the joint use of acquired data with these two sensors.

3.4 Conclusions

The Sentinel-MSI and Landsat-OLI sensors have similar characteristics, and their data together have the potential to support global coverage with medium spatial resolution and high temporal frequency for near-real-time information extraction for soil salinity monitoring in the context of major land use practices. Concerning the spectral resolutions and configurations, they were designed in such a way that there is a significant match between the homologous spectral bands. However, the spectral responsivities of both instruments are not identical for the homologous bands, so some differences are expected in the recorded reflectance values. The importance of these differences depends on the application and on the adopted approach to perform time series analyses or change detection. Probably, the extraction of biophysical or biophysiological variables using empirical and semiempirical approaches and remote sensing data can affect the results comparison. In this chapter, we analyzed exclusively the impact of dissimilarities caused by spectral response functions between these two sensors for high temporal frequency for soil salinity dynamic monitoring in an arid landscape. Knowing that the SWIR spectral bands are the most appropriate for soil salinity discrimination, modeling, and monitoring, only the land surface reflectances in these spectral bands are considered and converted to the SSSI and to the SEPM for soil salinity mapping. These three products were compared, and the impact of the sensors' (OLI and MSI) spectral response function differences was quantified. To achieve these, analyses were performed on two pairs of images acquired in July 2015 and August 2017 with 1-day difference between each other over the same study area, which is characterized by several soil salinity classes (i.e., extreme, very high, high, moderate, low, and nonsaline). These images were not cloudy, without shadow, and not contaminated by cirrus. They were radiometrically and atmospherically corrected, and bi-directional reflectance difference factors (BRDF) were normalized. To generate data for analysis, similarly to Landsat-OLI, Sentinel-MSI images were resampled in 30 m pixel size considering UTM projection and WGS84 datum. The comparisons of the derived products were undertaken using regression analysis ($p < 0.05$) and root mean square difference (RMSD). In addition to the visual analysis, kappa coefficient was used to measure the degree of similarity between the derived salinity maps using SEPM. The results obtained demonstrate that the two used pair's dataset, acquired during two different years over a wide range of soil salinity degrees ($2.6 \leq \text{EC-}_{\text{Lab}} \leq 600$ dS m^{-1}), had very significant fits (R^2 of 0.99) for the SWIR land surface reflectances and $R^2 \geq 0.95$ for SSSI and SEPM. Likewise, excellent agreements were observed between the two sensor products, yielding RMSD values less than 0.012 (reflectance units) for the SWIR bands and less than 0.006 for SSSI. The RMSD calculated for SEPM vary between 0.12 and 2.65 dS m^{-1}, respectively, for nonsaline and extreme salinity classes, reflecting relative errors varying between 0.046 and 0.005 for the considered soil salinity classes ($2.6 \leq \text{EC-}_{\text{Lab}} \leq 600$ dS m^{-1}). Statistical similarity between the derived salinity maps based on SEPM using kappa coefficient revealed an excellent agreement (0.94). Consequently, MSI and OLI sensors can be used jointly to characterize and to monitor accurately the soil salinity and its dynamic in time and space in arid landscape. However, with these positive results, preprocessing issues must be addressed rigorously before the Landsat-OLI and Sentinel-MSI data can be used together for soil salinity mapping and monitoring frequently in time.

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Modern Technologies for Diagnosis and Prognosis of Salt-affected Soils and Poor-quality Waters

4

A. K. Mandal

Abstract

Soil salinity and brackish groundwater are primary concerns for reduced productivity of 953 million ha in the world. In India, 6.73 M ha of salt-affected soils (SAS) is distributed in 15 states and 13 agroclimatic regions. Salt deposition at low topographic zones, high evaporation in arid zone, salty parent materials and brackish ground use in peninsular plain, and inundation of saline seawater in coastal areas are primary processes controlling genesis and distribution of SAS. Canal irrigation practices have contributed to waterlogging, soil salinization, and losses of soil productivity in poorly drained soils. Remote sensing data with improved spatial and spectral resolutions has facilitated detection and delineation of SAS with limited ground truth and soil studies. Using high-resolution remote sensing data, prognosis of soil salinity was studied to quantify soil salinization processes in canal command areas integrating topography, hydrology, and aquifer characteristics. Spatial variability of sodic and saline soils with salty groundwater was studied at farm scale at experimental farms. Visual and digital analysis of remote sensing data facilitated the identification of strongly salt-affected soils by high spectral reflectance of salt crusts from barren surfaces. High energy absorption in the SWIR band enabled identification of waterlogged soils in canal-irrigated areas with poor natural drainage. Temporal dynamics of salty surfaces, vegetation, and normalized difference vegetation index (NDVI) data during June, March, and October seasons were used for SAS with poor-quality or high RSC groundwater. Mixed spectral signatures for salt crusts, moderate cropping density, and surface wetness in moderately and slightly sodic soils are authenticated by ground truth study. Thermal band was used for salty soils and sand dunes showing close spectral signatures in visible range. Natric horizon formation, clay illuviation, iron and manganese mottles, higher moisture content, and

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precipitation of subsurface calcareous materials are typical soil-forming processes in sodic soil. Chemical analysis indicated high pH, exchangeable sodium percentage (ESP), and sodium adsorption ratio (SAR) values and the dominance of carbonate and bicarbonates of sodium. High moisture content and salt saturation (commonly saline soils of sodium chloride and sulfate salts) are typical features associated with waterlogged (surface ponding) soils and high water table depth (potential waterlogging). Periodic irrigation with water of high pH, SAR, and RSC (residual sodium carbonate) values favored the formation of salty soil profiles in arid and semiarid regions. High clay contents, smectite clay minerals, critical ESP (5 or more), and salty groundwater are primary constraints of black soil in the peninsular plains. The complex saline-sodic soils of alluvial (A), aeofluvial/arid (B), and others (H) are classed as sodic. Soils of coastal (D), deltaic (C), and mud flats/mangrove swamps (G) were classified as saline. Benchmark salt-affected soils were identified for monitoring in agroclimatic and physiographic regions. The largest areas (67% and 75%) of SAS lie in the arid to semiarid (300–1000 mm rainfall) and strong hyperthermic (25–27.5 °C) temperature zones and in the Pleistocene and Recent (39%) geological formations. Recent IRS data (years 2010–2013) revealed 315,617 ha of SAS lies in 18 districts of Haryana state. Attempts were also made to update similar databases for Uttar Pradesh and Gujarat states.

Keywords

Salt-affected soils · Soil salinity · Sodicity · Waterlogging · Remote sensing · Saline/sodic groundwater · SAR (sodium adsorption ratio) · RSC (residual sodium carbonate) · ESP (exchangeable sodium percentage) · Soil profile · Diagnosis and prognosis

4.1 Introduction

Accumulation of excess soluble salts in soils has led to the formation of salt-affected soils that adversely affect plant growth and crop yield. The main causes of salt accumulation include capillary rise from subsoil salt beds or from shallow brackish groundwater, besides other factors such as the indiscriminate use of irrigation water of variable qualities, weathering of rocks and minerals that brought down salts from the upstream to the plains by rivers and subsequent deposition along with alluvial materials, while the ingress of seawater along the coast, salt-laden sand blown by sea winds, and lack of natural leaching due to impeded topography in arid and semiarid regions also caused soil salinization. Higher proportion of alkaline salts alters soil reaction (pH) and influences the physical and chemical properties and the exchangeable cations content in particular. These salts influence osmotic and ion toxicity causing nutrient imbalances and thus are unfavorable for sustained crop production. The presence of excess neutral salt essentially influences solute transport and availability of selected macro- and micronutrients required for plant growth. Globally, 20% of the irrigated land (450,000 km^2) is salt-affected and about 2000–5000 km^2 land lost production every year as a result of salinity (UNEP 2009). In South Asia, the annual economic loss is estimated to be US$1,500 million due to salinization (UNEP 2009). In the tropical countries, soil salinity is a serious problem affecting crop production, plant growth, and soil and water quality leading to soil and environmental degradation. In Africa, a serious impact on economy has been reflected on average loss on agriculture from 28%–76% as a result of land degradation. In India, the average production loss from such degradation varies from 40% in wheat, 45% in rice, 63% in cotton, and 48% in sugarcane (Joshi and Agnihotri 1984). Based on various studies, the Central Soil Salinity Research Institute (CSSRI) (2000) reported that the alkali land reclamation schemes operated in Haryana, Punjab, and Uttar Pradesh states (Trans-Gangetic plain) brought changes in cropping intensity by 25% in paddy, 10% in wheat, 21% in pulses, and 10% in cotton. The economic benefit accrued from the sodic land reclamation programs showed the improvements of B:C (benefit-cost) ratio to 1.89 and 1.80 for rice and wheat, respectively (Thimmappa et al. 2013). Soil analytical data of reclaimed sodic soils showed prominent changes in soil pH and concurrent increase of organic carbon that showed improvement in fertility status (CSSRI 2000, 2007). The use of flow method of irrigation in poorly drained areas caused the emergence of waterlogging and secondary salinization that caused losses in productivity for rice (42%), wheat (38%), and sugarcane (61%) crops (Samra et al. 2006). Due to the use of salty groundwater (60–70% of TGA) for irrigation, secondary salt enrichment in soil profiles occurred along the Ghaggar and Markanda river plains (Manchanda 1976; Gupta 2010; Phogat et al. 2011). Present status and selected modern technologies for diagnosis and prognosis of salt-affected soils and poor-quality waters have been discussed in this chapter.

4.2 Categories of Salt-affected Soils

Five categories of salt-affected soils were identified based on the nature and composition of salts at global scale (Szabolcs 1989). These are saline enriched by natural salts, alkali with higher Na_2CO_3 and $NaHCO_3$ content that favor alkaline hydrolysis, gypsiferous with excess gypsum ($CaSO_4,2H_2O$), calcareous rich in the precipitated calcium carbonate ($CaCO_3$), magnesium with magnesium ($MgCO_3$) and sodium carbonate (Na_2CO_3), acid sulfate saturated with pyrite and jarosite (ferric and aluminum sulfates), and others including strongly degraded subsoil and potential salinity in irrigated region. In Eastern Europe, these soils were known as Solonchak, Solonetz, and Solod. The alkali soils of Europe and erstwhile USSR showed a good A horizon and a *natric* (sodic) subsurface B horizon. In India, these soils are known as *Kallar* or *Thur* in Punjab and Haryana, *Usar* or *Reh* in Uttar Pradesh, *Luni* in Rajasthan, *Khar* or *Kshar* in Gujarat and Maharashtra, *Chhouddu* or *Uppu* in Andhra Pradesh, *Choppan* in Karnataka, etc. The US Soil Salinity Laboratory (Richards 1954) proposed criteria for distinguishing sodic with saline and saline-sodic soils based on the critical limits of electrical conductivity (ECe) of saturation extract, ESP (exchangeable sodium percentage), and soil reaction (pHs) of saturated soil paste. The Soil Science Society of America (1987) used ECe and SAR (sodium adsorption ratio) as criteria for classification of salt-affected soils. The Central Soil Salinity Research Institute (CSSRI) proposed pH 8.2 as critical limit for initiation of soil sodicity and alkalinity following characterization of alkali soils of the Indo-Gangetic alluvial plain (IGP) (Agarwal and Yadav 1956). Later, Abrol et al. (1980) also reported that the adverse effect of soil sodicity on crop growth initiates at pH 8.2. Similarly, Balpande et al. (1996) proposed the critical limit of ECe to be 2 dS m^{-1} and ESP 5 for sodic vertisols showing higher clay content and smectite mineralogy. Australian workers proposed soil physical properties such as low hydraulic conductivity as a critical factor that affects plant growth in sodic soils. Soil characterization revealed that ESP 6 was the limiting value that impaired soil physical properties in a swell shrink soil in Australia (Northkote 1979). In India, broad categories such as saline and sodic were identified for reclamation and management purposes (Abrol and Bhumbla 1978; Abrol et al. 1988). The diagnostic features of these soils are described below.

Saline soils are appearing as salt patches with white encrustation on the soil surface commonly occurring in the lower landscape position. Due to high salt content, high osmotic pressure, and ion toxicity, these soils do not support normal growth of agricultural crops. These are also appearing in the irrigated areas along with waterlogging. The prolonged use of saline groundwater for irrigation also caused in situ soil salinity development in the arid and semiarid regions. These soils also exist along the seacoast as a result of saline seawater inundation, causing high soil salinity at the root zone. The soil chemical analysis data indicated dominance of neutral salts such as chlorides and sulfates of sodium, calcium, and magnesium higher than the prescribed limit. The pH of the saturated paste lies <8.2, and electrical conductivity exceeds 4.0 dS m^{-1} at 25 °C. These soils showed higher (>10) sodium adsorption ratio (SAR) in general.

Field studies of alkali soil showed bleached color, strong structure (blocky/prismatic/columnar), iron and manganese mottles, concretions/nodules of calcium and magnesium, fine-textured silt/clay layer (natric) at subsurface depth, moderate to strong/violent effervescence on application of dilute HCl, and pink color on application of phenolphthalein indicator. Alkaline pH (>8.2) affects plant growth and crop yield, while poor (dispersed) soil physical properties and internal drainage caused the imbalance of nutrient availability. High carbonate and bicarbonate of sodium, calcium, and magnesium and high sodium adsorption ratio (SAR) resulted in high exchangeable sodium percentage (ESP > 15).

4.3 Status of Salt-affected Soils: Global and National Scenarios

According to the FAO/UNESCO soil map of the world, 831 million hectares of land (6.5%) is affected due to soil salinization and alkalization (FAO Soil Map of the World 1974–1980). Later Szabolcs (1989) estimated 953 M ha based on the compilation of salt-affected soils of the world. The worst affected areas include Africa, Asia, Australia, Europe, Latin America, the Near East, and North America (Koohafkan 2012). Survey in Australia reported that 2 M ha (20,000 farms) is affected due to climate changes and 10% of Western Australia is seriously endangered by soil salinity/alkalinity of primary and secondary origin (Australian Bureau of Statistics 2002; McFarlane 2004). Keeping in view the large-scale variability of salt-affected soils and scale of mapping, FAO (2008) again reported harmonized data of salt-affected lands to be 434 M ha to be sodic and 397 M ha saline for planning and management purposes.

Systematic mapping and assessment of salt-affected soils (SAS) in India involves spatial measurements, field and laboratory studies, and reconciliation to arrive at a figure of 6.73 million hectares which is distributed in 15 states and 13 agroclimatic regions (CSSRI 2007; NBSS and LUP 2006; NRSA 1997, 2008). The saline (2.95 M ha) and sodic (3.77 M ha) soils are distributed in seven physiographic regions (Mandal et al. 2010). The occurrence of salt-affected areas is primarily influenced by rainfall, and about 29.4%, 26.2%, and 19.4% SAS exist in the ranges between 500 and 800 mm, 1000 and 1500 mm, and 300 and 500 mm, respectively. These soils are associated with a wide range of parent materials, most importantly, in Pleistocene and Recent origin (38.9%), Archean Schists and Gneisses (9.5%), and Deccan and Rajmahal Traps (7.8%), respectively (Mandal et al. 2011).

The irrigation through groundwater is a common practice for growing arable crops in the arid and semiarid regions. The water quality is of primary concern as on an average 25% poor-quality water is used in these regions for crop production. The distribution figures of saline groundwater in Rajasthan (41.2%), Haryana (25.9%), and Gujarat (12.4%) states warrant necessary inputs for management (Manchanda 1976; HSMITC 2001; Gupta 2010), while the extent of alkaline groundwater areas in Punjab (54%), Rajasthan (35%), Haryana (30%), and Gujarat (28%) states showed necessity for reclamation. The complex saline-alkali water is prevalent in Gujarat (52%), Rajasthan (49%), Haryana (46%), and Punjab (24%) and needs special care for crop production. On the other hand, the expansion of canal irrigation network in arid and semiarid regions caused emergence of salinity and waterlogging problems in un-drained areas.

4.3.1 History of Soil Mapping in India Through Remote Sensing

In India, systematic mapping of soil salinity was originated at the Central Soil Salinity Research Institute at Karnal under the Indian Council of Agricultural Research (ICAR) New Delhi collaborating with the National Bureau of Soil Survey and Land Use Planning (ICAR) Nagpur and National Remote Sensing Centre (DOS) Hyderabad under the Ministry of Defense, Government of India. A methodology for soil salinity mapping on a reconnaissance scale (1:250,000 scale) was developed using remote sensing data in conjunction with ground truth survey and soil and laboratory studies (Sharma and Mandal 2006; NRSA 2008; Mandal and Sharma 2010; Sharma et al. 2011). Regional-scale mapping of soil salinity was carried out for coastal areas of Gujarat state using Landsat TM data supported by ground truth (Joshi and Sahai 1993). Soil sodicity in Uttar Pradesh state was mapped on 1:50,000 scale integrating Indian Remote Sensing data (IRS LISS II) with soil profile studies (Saxena et al., 2004). Attempts were also made for digital image classification of soil degradation features combining field data and laboratory analysis (Mitternicht and Zinck 1997). Singh et al. (2010) suggested reconciliation and harmonization to estimate complex salt-affected soils.

Soil salinity map of Haryana indicated 52% of salt-affected soils are distributed in central Haryana covering Karnal, Kurukshetra, Panipat, and Sonepat districts (Mandal and Sharma 2005). Interpretation of Landsat images showed old levees, relict flood plain, and poorly drained low-lying flats are common topographic zones with salt infestation along the Gangetic alluvial plain (Manchanda and Iyer 1983). Introduction of canal irrigation from Western Yamuna Canal (WYC) in Haryana during the 1950s accentuated upward movement of salt by rising water table (Singh et al. 2010).

4.3.2 Traditional Methods: Field Assessment and Laboratory Characterization of Soils

Metternicht and Zinck (1997) combined digital analysis with field and laboratory analysis data for mapping sodium- and salt-affected soils. They concluded that the main causes of spectral confusions, masking different soil salinity-alkalinity degrees, were the type and abundance of salt-tolerant vegetation cover, topsoil texture, and other field properties. Joshi and Sahai (1993), Verma et al. (1994), and Sharma et al. (2000) used a similar approach combining remote sensing, ground truth, and soil analysis data for mapping coastal salt-affected soils in Saurashtra (Gujarat state) and inland salt-affected soils of Uttar Pradesh state. Such methods are laborious and need concerted efforts for image analysis, ground truth, soil sampling, and laboratory analysis of soil and water to integrate for mapping but produce results and classified outputs of salt-affected soils with higher accuracies. Classification of soils for salinity/alkalinity classes, such as slight, moderate, and strong, is useful for deciding precise soil reclamation and management options.

4.3.3 Modern Tools and Techniques for Diagnosis and Assessment of Salt-affected Soils

Due to spatial variability and dynamic nature, the mapping of salt-affected soils is difficult using traditional methods of surveying, soil sampling, and laboratory estimations. Remote sensing data with adequate spatial and spectral resolutions is widely used in detection, delineation, and monitoring of salt-affected and waterlogged soils in a time- and cost-effective manner (Saxena 2003; Rao et al. 1998; Shrestha 2006; Dwivedi 2006; Mandal and Sharma 2013). Initially, the aerial photographs were used for mapping salt-affected soils using visual interpretation approach which is based on the differentiating tone, texture, size, shape, and patterns of image elements. With the advent of digital technology and launching of the first Earth Resources Technology Satellite (ERTS 1) later renamed as Landsat 1, the mapping and monitoring of earth resources such as salt-affected soils become quite reliable and efficient. Subsequently, satellites with improved spatial and spectral resolution in Landsat, IRS, and SPOT series were included to enhance mapping efficiency (Singh et al. 1977, 1983; Venkatratnam 1984; Saxena 2003; Mandal et al. 2016). Mougenot et al. (1993) could easily identify barren salt-affected soils by high reflectance in the visible range, while thermal, infrared, and microwave data were also used to distinguish hygroscopic salts and vegetation-covered soils (Howari 2003). Howari et al. (2002) used spectroradiometry studies in visible and near-infrared range to quantify spectral properties of salt-affected soils with variable salt composition. Srivastava et al. (2016) also reported 1300–2400 nm bands as the optimum range for studying salt-affected soils. Recently, Allbel and Kumar (2013), Wu et al. (2014), Scudiero et al. (2014), and Ali et al. (2015) used high-resolution (MODIS) remote sensing data for quantification of soil salinity/sodicity with limited ground truth (land use), field, and laboratory soil studies. Khan et al. (2005) integrated ratio/brightness/salinity indices and spectral properties for digital classification of hydro-saline land degradation in the Indus basin, Pakistan.

4.4 Spectral Characteristics of Salt-affected Soils

The salt-affected soils are typically characterized by either high pH or high ECe or both. Prominent reflectance of salt-covered areas was shown in the visible part of the spectrum (Mougenot et al. 1993). The False Color Composites (FCC) prepared from red, green, and blue bands showed that these soils appeared as bright white to dull white patches associated with the brown/reddish color representing green vegetation. Bands in the middle-infrared range provide information on soil moisture often associated with salts, and the reflectance differs on the type of salt. Limited studies have been reported on the spectral behavior of salt-affected soils. Well-developed saline efflorescence and crusts are associated with high reflectance in visible and near-infrared bands and high DN (digital number) values in the digital data with a high value of brightness index (Berenger 1985; Rao et al. 1995). Halite occurrence of salt-affected soils was indicated by white gray tones in satellite data (Sharma and Bhargava 1987). Middle-infrared bands with water and OH- absorption band allow differentiation of chloride (as halite) and sulfates (as gypsum) soil surfaces if both are dry (Mulders 1987; Saha et al. 1990). The thermal infrared band is commonly used to estimate moisture and salinity. It also recognizes features of sulfates, phosphates, and chlorides showing high energy absorption (Mulders 1987). Mandal and Sharma (2011a) reported variable reflectance of salty, waterlogged, and sandy soils in IRS LISS II data representing irrigated areas of IGNP (Indira Gandhi Nahar Pariyojana). Mandal et al. (2016) identified reflectance in IRS LISS III data representing irrigated sodic soils with good and sodic groundwater in Kurukshetra district of Haryana.

4.4.1 Role of Vegetation in Detection of Soil Salinity

Contrasted association of vegetation and bare soils is useful for salinity detection in agriculture (Richardson et al. 1976; Everitt et al. 1977). An inverse relationship was reported between spectral reflectance and soil salinity of salt-affected soils. Since salt content induces less plant cover, decreased density, low LAI (Leaf Area Index) and plant height, the salin stressed vegetation showed a reddish or dark red shift on standard color composite data (Everitt et al. 1977; Colwell 1983). An infrared vegetation index (IR−NIR/IR+NIR) was proposed to detect canopy moisture influenced by salinity which is considered as superior to normalized difference vegetation index (NDVI) = NIR−IR/NIR+IR (Hardinsky et al. 1983). Besides, salinity index [$SI = (G \times R)^{1/2}$], normalized difference salinity index ($NDSI = (R - NIR)/(R + NIR)$), and brightness index ($BI = (R^2 + NIR^2)^{1/2}$) are also used for differentiating spectral nature of salty soils. Kalra and Joshi (1994) reported spectral reflectance characteristics of salt-affected soils in arid sandy region of Rajasthan (under *Thar* desert) and found highest reflectance from natural salt-affected soils showing surface salt encrustation followed by sodic soils formed due to the application of high residual sodium carbonate/bicarbonate containing irrigation water, natural saline soils, and saline soils developed from irrigation with saline groundwater. Soil texture, pH, $CaCO_3$, and organic matter percentage together accounted for 29.6% variation in the maximum reflectance percentage value, out of which pH accounted for more than half (14.2% variation).

4.4.2 Landscape Characteristics

Good correlation was observed between soil distribution and geomorphological shapes (Rafiq 1976; Manchanda and Iyer 1983; Manchanda 1984). Relative elevation is one of the most evident landscape features in relationship with salinity and moisture provided by saline and shallow groundwater table. Salt efflorescence occurs with more rapid evaporation on the margin than in the center of depressions with vertical and lateral salt variations (Menenti 1984).

4.4.3 Type and Degree of Soil Salinity

Strong and medium salinity was detected in salt-affected soils of the Indo-Gangetic Plain (Singh et al. 1983). High spatial variability of salt quantity was found characteristic of most salt-affected soils (Mougenot et al. 1993). Satellite data facilitate detection and mapping of salts and high sodicity (high pH and SAR) due to high reflectance (Colwell 1983). Standard False Color Composites (FCC) with combination of red (band 3), green (band 2), and blue (band 1) indicated bright white patches with smooth image texture representing strongly sodic soils and dull white to strong brown for moderately sodic soils (Rao et al. 1995). Combination of Landsat TM bands (1, 2, 4, 5, 6, and 7) was used for differentiating salt- and sodium-affected soils with limited field observation and laboratory determination of soils (Metternicht and Zinck 1997). Howari (2003) reported distinctive reflectance patterns of salts using Landsat Enhanced Thematic Mapper (ETM^+), airborne visible/infrared imaging spectrometer (AVIRIS), color-infrared (CIR) aerial photo, and high-resolution field spectroradiometer (GER3700).

4.4.4 Remote Sensing for Monitoring Salt-affected Soil

The satellite data due to its repetitive coverage provides temporal information of salt-affected soils by acquiring data at suitable time and scale. It also provides information regarding the dynamics of salt-affected soils over a period of time. A team of experts from the National Remote Sensing Agency (NRSA), Hyderabad, studied 130 km^2 of the Sangrur district of Punjab state during 1975 and 1981 and found that an area of 4.33 km^2 of salt-affected soils was reduced due to the intensive reclamation practices. Using aerial photographs and Salyut 7 data, Rao and Venkatratnam (1987) monitored salt-affected soils in the Ukai Kakrapar command area covering 21,203 ha in Bharuch district. Aerial photograph of December 1977 showed 36% of the area was occupied by various categories of salt-affected soils, while Salyut data of April 1984 showed 79% of the area under salt-affected soils indicating twofold increases of salty area. Landsat MSS and TM data for 1975 and 1986 revealed significant reduction of salt-affected areas in Karnal and Jind districts of Haryana (Dwivedi et al. 1987), while remote sensing technique showed an increase in 15% over a period of 28 years in Aligarh district of Uttar Pradesh (Saha et al. 1990). NRSA (1995) reported a significant shrinkage of salt-affected soils over a period of 18 years in Sharda Sahayak command area in Uttar Pradesh.

4.4.5 Visual vs. Digital Methodology for Image Interpretation and Analysis

Two methods, viz., visual interpretation and digital analysis, of remote sensing data are commonly used to derive information on salt-affected and waterlogged soils. Visual interpretation of these soils involves satellite image interpretation using variable tone, texture, shape, size, and pattern of the image elements, while digital analysis involves generation of spectral signature of training areas, separation analysis generating scatter plots and classification of digital data registering training sets using suitable algorithms, and finally assessing accuracy of estimate. The imageries were initially analyzed with the help of topographical maps, published reports, and other ancillary information to delineate broad categories of salty lands. Again, each unit is subdivided into subunits based on the drainage density, vegetation cover, or land use or land cover. These units were transferred onto the base map prepared from the Survey of India topographical maps at suitable scale. Representative areas were selected for ground truth collection, and field visits were conducted to collect data on the soil topography and other site characteristics, and soil samples were collected from soil profile studies for laboratory analysis. The preliminary interpreted maps were modified in the light of field data and soil chemical analysis data to prepare final map of appropriate legend. Mapping of salt-affected soils was carried out in Haryana state at 1:250,000 scale using visual interpretation of photographic prints (black and white, color composites) and correlated with field studies (Sharma and Bhargava 1987). False Color Composites (FCC) of IRS LISS II data was used to delineate waterlogging and soil salinity in irrigated region of IGNP, Rajasthan state, India (Mandal and Sharma 2001).

Visual interpretation of Landsat TM imagery was integrated with field studies and soil physicochemical characteristics, to map the salty soils at 1:250,000 scale for 15 states. To accomplish the task, the National Remote Sensing Agency (NRSA), Hyderabad, collaborated with the National Bureau of Soil Survey and Land Use Planning (ICAR), Nagpur; the Central Soil Salinity Research Institute, Karnal (ICAR); and other central and state government organizations. The physiography, nature (saline/sodic/saline-sodic), magnitude (slight/moderate/strong), and extent (<1/3, 1/3–2/3, and >2/3) were used as map units for characterization of salt-affected soils.

The digital data were analyzed and interpreted using special image processing software. These data were processed at various stages for geometric correction, radiometric normalization, and image enhancement using different techniques. Computer-aided delineation of salt-affected soils using remote sensing data has been demonstrated by various workers (Venkatratnam and Rao 1977; Singh and Dwivedi 1980; Singh 1982; Saha et al. 1990). Maximum likelihood classifier was used for supervised image classification of Landsat TM data while mapping wastelands in Aligarh district of Uttar Pradesh (Saha et al. 1990). Landsat bands 3, 4, 5, and 7 highlighted successful separations of salt-affected and surface-waterlogged soils on the basis of spectral response and training statistics.

4.5 Case Studies for Assessment of Soil Salinity Using Traditional and Space Technology

4.5.1 Waterlogged Saline Soils in IGNP (Phase I) Rajasthan

IRS (Indian Remote Sensing) LISS II data are interpreted for the identification of waterlogged areas (ponded water), salt-affected soils (salt efflorescence), and high water table zones (potential waterlogging zones) in the Indira Gandhi Nahar Pariyojana (IGNP) command area followed by ground verification. False Color Composites (FCC) of bands 432 for February 1996, November 1996, and June 1998 on 1:50,000 revealed occurrence and seasonal dynamics of permanent waterlogging in low-lying flats and depressions. Due to less evaporation and more agricultural operation, waterlogging was higher during February. Prominent salt accumulation in November may be ascribed due to freshly precipitated salts. Seepage and accumulation of excess irrigation water through coarse sandy soils appeared to be primarily the reason behind waterlogging (ponded water). The secondary soil salinization occurred due to the capillary action of salts and high water table with high evaporative demand. Ground truth study also revealed the patchy crop stands with high water table (<1.5 m) depth and poor vegetative growth with fluctuating (1.5–6.0 m) water table depth indicating potentially sensitive areas for waterlogging. The soil properties showed moderate to high soil salinity in the control section of soil profiles. Field soil study data indicated medium to coarse texture, weak to moderately strong structure, weak consistency, low organic matter content, and abundant $CaCO_3$ nodules. Saturated soil paste indicated dominance of chloride and sulfate of sodium, calcium, and magnesium. Field studies also indicated the perched water table at shallow depth in fine-textured soils and a $CaCO_3$ layer at subsurface depth of soil profile and also question its suitability for traditional irrigated agricultural practices. The quality of pond water was extremely poor and unfit for reuse. The groundwater was saline in some areas but normally lies within the prescribed limit. The quality of drainage water was poor in highly salinized soils at depression areas and unsuitable for reuse. Moderate salinity in other drainage sites suggested its safe reuse if applied mixing with good-quality water. Suitable soil and water management practices were necessary for sustainable crop production in the command area (Mandal and Sharma 2011a).

4.5.2 Waterlogged Saline Soils in Lunkaransar Canal Areas of IGNP (Phase II) Rajasthan

Indian Remote Sensing (IRS LISS II) data on 1:50,000 scale showed prominent waterlogging as surface ponding in sandy flats and depressions along the Lunkaransar lift canal under the IGNP. The seasonal data revealed higher extent of waterlogging in February (1996) and mixed spectral signatures of high moisture content with poor crop stand in November (1996) and permanent waterlogging (close to the lift canal) in June (1998) data. Ground truth survey revealed the presence of shallow aquifer (water table depth <1.5 m) condition, patchy crop stand, moist soil profile, and soil salinization. The occurrence of fluctuating (1.5–6.0 m) water table depth during dry and wet cycles and poor cop stand in irrigated areas showed the presence of potential waterlogging zones. Moderate to high soil salinity was found at surface soil located in low-lying flats and higher salinity at subsurface depth (control section, 0.2–0.8 m) of soil profiles indicating initiation of secondary salinization. The layer of calcium carbonate was present at a depth below the surface. The chlorides and sulfates of sodium, calcium, and magnesium were dominant salts in the study area. The water quality of drainage effluents was extremely poor and may be used with good quality of water either in cyclic or mixing mode. The ponded and subsurface water quality is moderate and is fit for reuse (Mandal and Sharma 2013, 2014)

4.5.3 Waterlogged Saline Soils in Central Haryana

Salt-affected soils of Western Yamuna Canal (WYC) irrigation command were mapped using digital analysis and GIS. Sample strips were used to assign training sets while conducting supervised classification of Landsat TM data using ILWIS software. Five salinity classes were identified that showed an overall accuracy of 85.6%. Moderately and highly saline areas were easier to identify than the slightly saline areas. Combination of red and infrared bands was used for separating saline and sodic soils. A GIS overlay of thematic layers from the Survey of India maps on 1:50,000 was developed to generate a base map. The nonspatial data for soil physicochemical and salt composition were included as attribute table and were linked with the spatial data though a common geo-reference to prepare a relational database. Digitized spatial and attribute datasets were used as inputs to prepare the classified output as raster map. Thus, relating salinity classes with topology and soil attributes favors salinity management of irrigated areas (Sharma and Mandal 2006).

4.5.4 Salt-affected Soils in Upper Krishna Project, Karnataka

The Upper Krishna project in Karnataka aimed at providing canal irrigation to the chronically drought-prone areas of Gulbarga, Bijapur, and Raichur districts. The project irrigated 843,000 ha in two stages: 425,000 ha in stage I and 410,000 ha in stage II. Preliminary survey indicated that 27.6,000 ha area was salt-affected. Through visual interpretation, salty soils could be identified and classified in three classes, viz., moderate (<40% salt-affected), severe to moderate (40–75% affected), and severe (>75% affected). The severely salty lands were appearing as while salt crust on the IRS LISS III 1997 data, while mixed blue/green and white impressions and red mottles for crop covers were found in moderate salty soils. The total salt-affected areas were 21,906 ha in phase I. The spectral reflectance studies revealed correlation with ground soil salinity measurements limited to severely salt-affected soils. Attempts were made to classify image characteristics using brightness index, NDVI, and physiography data for mapping these soils with higher accuracy (IDNP 2002).

4.5.5 Waterlogging and Soil Salinity for Drainage Project, Gohana (Sonepat), Haryana

Satellite imageries (IRS IC, IB, SPOT, and Landsat-5 TM) for October 1988; January 1989; November 1994, 1995, and 1996; February 1996; and April and June 1996 were used to get insight in the dynamics of salinity and waterlogging under a subsurface drainage project site covering 5000 ha along the JLN feeder and Bhalaut branch of WYC (Western Yamuna Canal) in Sonepat district of Haryana state. Dynamics of salinization and waterlogging was established by digital classified satellite imageries at different crop seasons. Spatial interpolation was used for assessing spatial variability of soil salinity. The data on water table depth during June and October, elevation, soil pH, and ECe (dS m^{-1}) were used for assessing evolution of waterlogging and soil salinity (IDNP 2002).

4.5.6 Soil Salinity in Ukai Kakrapar Canal Command (Gujarat)

The Kakrapar canal was introduced in 1957 to irrigate 200,000 ha covering 12 *talukas* of Surat, Navsari, and Valsad districts of Gujarat (IDNP 2002). The area is broadly divided into seven river basin zones, and the extents of *Khar* (salt-affected) and unproductive lands covered 64,450 ha and 15,860 ha, respectively. In the coastal zones, the climate is subhumid to semiarid, and the soils are deep and clayey (40–60%) and showed low permeability. IRS LISS III-PAN merged data were used to study soil salinity along with the cadastral maps and soil physicochemical data such as pH, ECe, and ESP. About 37% areas suffer from soil salinity or sodicity or both (5%), and greenish/dirty whitish tones on the satellite data indicated salt-affected soils, of sodic or saline nature. The ESP of the highly sodic soils in Vertic Ustochrepts of south Gujarat showed positive correlation ($R^2 = 0.46$–0.47) with spectral radiance values of band 2 (green, 0.52–0.59 μm) and band 3 (red, 0.62–0.68 μm).

4.5.7 Soil Salinity and Waterlogging in Nagarjuna Sagar Project

LISS III April 2000 data was used to identify and map salty soils and waterlogged areas on 1:50,000 scale in 74,000 ha areas of Nagarjuna Sagar Project. The salt-affected soils usually appear in different tones of bright white to dull white with medium to coarse texture on FCC print in the background of normal soils due to the presence of salts. The waterlogged ponded areas appear on FCC image in various shades of dark blue to black tones with smooth texture. The salty soils are encountered at the lower slopes of the terrain and occupied 4% of the total study area. These are classified as saline-sodic classes and exhibited higher spectral reflectance value in band 3. "Moderately saline and moderately sodic" category of soils showed highest spectral reflectance values in IRS IC bands followed by "slightly saline and moderately sodic" and "slightly saline and slightly sodic," respectively (IDNP 2002).

4.5.8 Salt-affected Soils in the Sarda Sahayak Canal Command Areas Uttar Pradesh

Waterlogging and soil sodicity in Sarda Sahayak canal command areas in Uttar Pradesh state were studied using Landsat TM (1986) and IRS LISS II (1996) data on 1:250,000 and 1:50,000 scales, respectively. Depth-wise profile soil samples were collected from 19 Pedon in 12 blocks of Kanpur district. The soils of the district are derived from the alluvium deposited by rivers and are generally medium textured and poorly drained. The analytical data indicated that the pedons were alkali in nature with hard epipedon. The increase in the clay content of the subsurface layers is indicative of the processes of alleviation and an argillic horizon. The soils are slightly calcareous, the intensity of which increases at lower depths. The pH of the pedons was between 8.2 and 10.5. The ECe was as high as 16.7 dS m^{-1}. The SAR and ESP values indicated the level of sodification, and the major cations and anions are sodium, calcium, magnesium, carbonates, bicarbonate, and chloride. The CEC values increased with increase in clay content and ranged between 5.2 and 17.0 c mol. p^{+} kg^{-1}. The physicochemical properties indicate the presence of an argillic and natric horizon with high value of chroma >2, due to reduced conditions in the mottled horizon, coupled with Ustic moisture regime and calcic horizon in lower depth. Over the district, alkali lands are widespread, and very severe alkalinity (pH > 10.2) covers 560 km^2 area while severe (pH 9.6–10.1) covers 330.6 km^2 and moderate (pH 9.1–9.5) 156.2 km^2, and marginal lands (pH 8.6–9.1) are present in 193.2 km^2; a total of 736 km^2 were affected by soil sodicity (11.9%) of the TGA (6177 km^2) (CSSRI 1992–1996).

4.5.9 Salt and Water Regimes in Benchmark Salt-affected Soils in India

Benchmark salt-affected soils were studied in 14 irrigation commands including coastal soils of Ramanathapuram and Andaman and Nicobar Islands (A&N) of India. Thirty benchmark soil profiles were studied to know and understand seasonal salt dynamics and composition in varied agro-eco-regions of the country. Based on the profile characteristics of salt-affected soils, GPS-assisted benchmark sites were marked in 11 irrigation commands, such as the Western Yamuna, Bhakra and Jawaharlal Nehru canal commands in Haryana, Agra, Sharda Sahayak and Upper-Ganga canal in Uttar Pradesh, saline vertisols in Narmada Sagar (MP), secondary salinity in IGNP (Rajasthan), Krishna Western and Cauvery (Undi) deltas, Nagarjuna Sagar in AP, Tungabhadra (Gangawati) in Karnataka and coastal saline soil of Ramanathapuram and A&N Islands. (CSSRI 2002–2005) (Murthy et al. 1980)

4.5.10 Waterlogged Sodic Soils in Gandak Command (Bihar)

The interpretation of IRS ID LISS III imageries with ground truth and soil study data indicated small white spots of alkali soils in cropped and waterlogged areas of Gandak command covering Gopalganj and Siwan districts of Bihar. The alkali soils were noticed in abandoned land, old mango orchards, and small patches in arable areas. The calcite and dolomite in soil produced CO_3^{2-} and HCO_3^{-} ions and accumulate in poorly drained areas. The high sodium ions favored developing high SAR, soil alkalinity, and pH. The alkali soils were characterized as very deep with pale brown to light yellowish brown soil matrix and few to common yellowish brown mottles in the subsurface horizons. These soils can be reclaimed with low (4 t ha^{-1}) doses of gypsum or pyrites and better management practices (Sharma et al. 2011).

4.5.11 Sodic Soils in the Gangetic Alluvial Plain of Etah District, Uttar Pradesh

Sodic soils are widespread in the alluvial plain of Ganges basin located in Uttar Pradesh. The integrated approach of IRS LISS II data with soil survey revealed sodic soils (43,040 ha, 9.7%) in the old, recent (7594 ha, 1.7%) and active alluvial plains (2102 ha, 0.5%) of Etah district. High pH and ESP values in sodic soils of alluvial plains indicated Na^+ ion saturation of soil exchange complex and favorable conditions for the formation of natric horizon, platy soil structure, and precipitation of $CaCO_3$ as nodules and concretions. In the recent alluvial plain, sodic soils were characterized by moderate pH and ESP values and salt contents for Na^+, CO_3^{2-} + HCO_3^-, and $CaCO_3$ in subsoil layers and blocky soil structure. In active alluvial plain, sodic soils were characterized by low to medium pH (8.8–9.6), ESP (23), Cl^-, CO_3^{2-}, and nodular lime contents. The typical characteristics of sodic soils located in varied geomorphic location are useful information for reclamation strategies in Etah district of Uttar Pradesh (Saxena et al. 2004).

4.5.12 Sodic Soils of the Shivari Experimental Farm, Lucknow, Uttar Pradesh, India

CSSRI experimental farm Shivari was surveyed for characterization and classification of sodic soils. Moderately to severely sodic soils were identified in three farm terraces, viz., >120.6 m, 120.6–119.8 m, and <119.8 m MSL. Typical characteristics of sodic soils are light color, sandy loam to clay loam texture, strong subangular to angular blocky structure, and imperfect drainage leading to restricted air and water movement in B and C horizons, respectively. The clay content in B is 1.3–1.6 times higher than the upper layers, thus indicating illuviation. pH is strongly alkaline (9.4–10.9) and increases with depth. ECe is high 10.6–15.2 dS m^{-1} at surface and decreases with depth. CO_3 and HCO_3 of Na are the dominant salt in the saturated paste. High SAR caused low infiltration rate, and ESP values <20 at surface soil indicated its status after reclamation. These soils showed variable ESP (47–91), pH, and significant lime nodules (250–500 g kg^{-1}) at a depth below the surface. Organic matter content is low (0.16–0.62%) in general. The soil properties showed overall poor productivity and also indicate application of suitable dosages of gypsum and proper soil management for potential use in arable crops and horticulture and forestry purposes. Illite, chlorite, kaolinite, mixed layers, and smectite are dominant minerals along with quartz, feldspar, mica, and amphibole. These soils are classified as associations of fine-loamy, mixed, hyperthermic, Natrustalfs, and Haplustepts (Sharma et al. 2011).

4.5.13 Soil Salinity and Groundwater Quality in Nain Farm, District Panipat, Haryana State

Salt-affected soils of experimental farm at Nain village (Panipat district and Haryana state) were surveyed, characterized, and classified for reclamation and management. Historically, the farm area (10.8 ha) was a barren, flat scrub land showing thick salt efflorescence/crust with high soil salinity at surface and saline groundwater. Located at the Indo-Gangetic alluvial plain under semiarid climate, the salty soils are highly variable and complex saline and sodic in nature. The presence of calcium carbonate as *calcretes* and iron oxides nodules as *ferricretes* indicated an irreversible precipitation of calcium, iron, and manganese in sodic soils under poor drainage condition. These soils are characterized by variable soil texture, the absence of distinct horizon development and *Ustic* soil moisture regime and are classified as Haplustepts under the USDA Soil Taxonomy. Highly saline soils are classified at phase level. Sodic character is shown at the subgroup level following modified classification by Verma et al. (2007). The non-availability of good-quality water (canal/tube well) restricted its use for arable cropping. Seepage and accumulation of salty parent materials caused high soil salinization in soil profiles at lower topographic zone. Using grid sampling method, the spatial variability was studied to assess variability soil salinity/alkalinity and soluble ions. The dominance of chloride and sulfates of sodium, calcium, and magnesium in saline soils and the presence of carbonates and bicarbonates in sodic soils showed necessity for salt leaching and gypsum treatment for reclamation. Soils with low to moderate salinity are suitable for growing salt-tolerant varieties with necessary soil and water management practices. Highly saline and sodic soils may be used for fishery development or forestry purposes. The quality of groundwater at shallow depth (~24 m) is saline and unfit for irrigation. It may be used in cyclic or mixed mode with good-quality water. The quality of drain water is good but is available in monsoon season only. These soils are also used for brick kilns and industrial development purposes such as thermal power generation, fertilizer manufacturing (NFL), and oil refinery (IOC) plants in nearby areas. In areas where good-quality irrigation water is available, these lands were used for growing rice and wheat (Mandal et al. 2013).

4.5.14 Prognosis and Characteristics of Salty Soils of South-West Punjab, India

The evidence of secondary salinization in south-west Punjab was studied using IRS LISS III March 2000 data on 1:50,000 scale. The study area covered Bhatinda, Giddarbaha, Malaut Mandi, Lambi, Dabwali, Muktsar, and Faridkot areas. The salty soils appear in white to white blue tones on the images and were found mostly along the Sirhind main canal. Waterlogged soils were mapped by their dark and uneven appearance on the imagery. Seepage from Sirhind and Rajasthan Feeder canals and overuse of irrigation water for crops have brought about the rise of water table and eventually waterlogging and secondary salinization. The depth to water table in the study area was 11 m in 1981 and is close to the surface. It has forced the farmers to give up the cultivation of cotton and grow rice instead. Three categories of risks were identified, these were high water-table areas with onset of salinity and waterlogging, high water table areas with predicted soil salinity and waterlogging in the alluvial plain, Paleochannels, dune and inter-dune areas. The average increase in the areas under risks was 42% between 1997 and 2001. The physicochemical characteristics of salt-affected soils of south-west and central Punjab showed complex saline and sodic nature. Coarse texture soils under canal irrigation showed development of waterlogging and soil salinity. The presence of concretionary calcium carbonate at subsurface depths caused poor internal drainage and favored waterlogging. Suitable management options for growing salt resistant crops, proper water management practices and alternate land uses, such as horticulture and forestry plantations are suggested. The quality of surface water samples was also poor (Mandal 2014).

4.5.15 Extent, Nature and Management of Salt-affected Soils in Gujarat State

The state of Gujarat, located on the western edge of the Indian subcontinent, has a large part of its land surface under salinity/sodicity. To assess extent, nature, and characteristics of these soils, surveys were conducted and remotely sensed data collated. Soil profiles (419 Nos.) were examined from nine soil survey units viz, South Gujarat and the Panchmahals, Mahi command, Bhal, Khara Pat, coastal areas of Jamnagar, Rajkot, Amreli and Junagadh, area under the Nal Sarovar, south Gujarat, areas adjoing the Rann and Katchh. Based on the field and laboratory analytical data, 27 representative profiles have been classified into subgroup level under the Soil Taxonomy. The primary soil units were classified under the Aridisols, Inceptisols, Vertisols, and Entisols orders. Based on the prominent soil morphology, these soils were further classified as Natrargids, Camborthids, Salorthids, Calciorthids, Halaquepts, and Ustochrepts at the subgroup level. A sizeable area of 16, 89, 860 ha (8.62% of TGA) in Gujarat is affected by salinity and sodicity. Salinity is major problem in Kachchh, Mahi command, Rann, and Panchmahal as a result of tidal ingress and secondary origin. Sporadic occurrence of alkalinity is found in Mahi command, Nal Sarovar, North and South Gujarat, Bhal, and the Panchmahals. Factors responsible for soil salinization include climate, irrigation system, irrigation practices, imperfect drainage, tidal ingress, and parent materials (Dubey et al. 1995).

4.5.16 Description and Characterization of Typical Soil Monoliths from Salt-affected Areas in Rajasthan

The study was undertaken to describe methodology for collection, preparation, and characterization of two soil monoliths, an alkali soil of Borai village Bharatpur district and an irrigated saline soil from Lunkaransar area Bikaner district, of

Rajasthan state for display and demonstration to users. Soil monoliths were collected from a profile pit measuring 1.8 m × 1.8 m × 1.5 m dimension using a wooden box of 1.2 m × 0.25 m × 0.1 m and 1.5 m × 0.25 m × 0.1 m dimensions at Lunkaransar and Bharatpur, respectively. The soil surface and the base of the box were repeated sprayed with adhesive containing acetone and cellulose. After clamping the box on the prepared column of the soil, it was detached from the soil mass by careful scrapping. The freshly separated side of the monolith was carefully brought to its natural state by exposing structural Peds color differentiation and concretions. The front side of the monolith was sprayed with a clear transparent adhesive for better preservation and display. The important features of the monoliths were annotated for display and presentation (Mandal and Sharma 2012).

4.6 Development of Computerized Database on Salt-affected Soils Using GIS

4.6.1 Digital Database of Salt-affected Soils in India on a Reconnaissance Scale

Salt-affected soils were mapped on 1:250,000 scale based on the interpretation of remote sensing data, ground truth studies, and laboratory analysis of soil samples for pH, ECe, and ESP. These soils covered 15 states (printed on 125 paper sheets) and contained voluminous data on spatial coverage, physiography, and categories of salt-affected soils. In the analog form, such data is difficult to handle by users of varied background and interest. For easy access, quick retrieval, and spatial analysis in multiple thematic layers, the analog maps were geo-referenced and digitized to develop theme layers of salty soils and a base map overlaying infrastructure (roads/railways), irrigation/drainage (canal/river), settlements (state/district capitals), and political/administrative boundaries. Soil salinity maps of 15 states were compiled in GIS to develop a composite map of India. An estimated area of 6.73 M ha was salt-affected soils; saline and sodic soil covered 2.9 and 3.7 M ha, respectively (Mandal et al. 2010).

4.6.2 Regional Databases for Western and Central India

Salt-affected soils occupy significant areas in western and central India manifested by the arid and semiarid climate, sandy/clayey soil texture, absence of natural drainage, and inadequate infrastructure and irrigation development. These soils are also potentially productive following reclamation and appropriate management. Based on the salt-affected soil maps of Rajasthan, Gujarat, Madhya Pradesh, and Maharashtra states, a composite (master) database showing the extent and distribution of salt-affected soils in western and central India was prepared (Mandal and

Sharma 2011b). Spatial data such as agroclimatic zones, physiography, climate, geology, and agro-eco-subregion was overlaid to show spatial relation with salt-affected soils. The saline soils were dominant in the arid (B), alluvial (A), and coastal (D) plains of Rajasthan and Gujarat, and sodic soils are located the peninsular plain (F) of Maharashtra and Madhya Pradesh. It occupied 2,596,942 ha (78%) in Rajasthan and Gujarat and 733,608 ha (22%) in Madhya Pradesh and Maharashtra and covered 3.3 million ha in the western and central region accounting 50% of the total salt-affected soils in India. The saline and sodic soils covered 2,069,285 ha (62%) and 1,261,266 ha (38%), respectively.

4.6.3 Peninsular Plain

State maps of salt-affected soils for Andhra Pradesh, Karnataka, Tamil Nadu, Kerala, and Orissa were integrated to prepare a composite database for peninsular plain using GIS (Mandal and Sharma 2009). Sodic soils (73%) are distributed in the peninsular (F) and alluvial plains (A) of Andhra Pradesh (20%), Tamil Nadu (37%), and Karnataka (15%). Saline soils (27%) were located in coastal (D), deltaic (C), and mangrove (G) regions of Orissa (15%) and Kerala (2%). Significant areas (69%) were distributed in three agroclimatic zones such as West Coast Plain and Ghat Region (ACR XI), Southern Plateau and Hills Region (ACR X, 26%), and East Coast Plains and Hills Region (ACR XII, 4.5%).

4.6.4 The Indo-Gangetic Plain

Indo-Gangetic Plain (IGP) of India has stretched from the Punjab to West Bengal state and is known for fertile soil and favorable climate for rice-wheat production. Soil salinization in IGP is a major concern due to loss of productivity. State maps of salt-affected soils for Haryana, Punjab, Uttar Pradesh, Bihar, and West Bengal were integrated in GIS to prepare composite database of IGP. The boundaries of 4 agroclimatic regions (ACRs) and 17 agroclimatic zones (ACZs) were used for regional planning and development of salt-affected soils using ILWIS-GIS. Soils were saline at the Lower and Middle Gangetic Plains and complex saline-sodic in the Upper and Trans-Gangetic Plains. The largest areas of salt-affected soils were recorded in the Upper Gangetic Plain (ACR V) of Uttar Pradesh followed by the Middle Gangetic Plain (ACR IV) of UP and Bihar, the Lower Gangetic Plain (ACR III) in West Bengal, and the Trans-Gangetic Plain (ACR VI) of Haryana and Punjab (Mandal and Sharma 2006).

4.6.5 Coastal Plains

Salt-affected soil maps for eight states (49 districts) were compiled to prepare a composite database for coastal region using GIS (Mandal et al. 2018). Saline

(1,828,361 ha, 73%) and sodic (673,008 ha, 27%) soils were distributed in D (38.8%), F (13.9%), G (13.4%), C (9.6%), B (6.5%), A (3.5%), and H (14%). Significant areas are distributed in Gujarat (50%), West Bengal (17.6%), Tamil Nadu (12.7%), Andhra Pradesh (7.6%), Orissa (5.8%), Andaman and Nicobar Islands (3.0%), Maharashtra (2.0%), and Kerala (0.8%) states.

4.7 Updating of Salt-affected Soils Database for Haryana State at Post-reclamation Stage

4.7.1 Significance of the Study

The first survey of salt-affected soils was initiated by identifying soil alkalinity and salinity problems in the Gangetic alluvium located at Etah district in Uttar Pradesh (Leather 1914). Patches of salt-affected soils were detected in the lower Ganges canal areas of Uttar Pradesh (Agarwal et al. 1957). Investigations revealed that salts are drained from the Himalayas and Siwalik through rivers/streams and are accumulated at the alluvial plains (Sidhu et al. 1995; Bhargava et al. 1980). The lack of adequate internal drainage in lower topographic regions prompted soil salinization (Bhargava et al. 1980). High evaporation during the dry season and lack of good-quality water for leaching caused salt accumulation in soil profiles. The coexistence of salt-affected soils and poor-quality groundwater in central Haryana is a primary constraint for agriculture (Yadav 2003). The use of poor-quality groundwater for irrigation increased salt buildup in soil profiles, which caused reduced productivity. Canal irrigation in un-drained areas has also accentuated waterlogging, formation of high water table, and secondary salinization in soils. The erratic rainfall and temperature patterns not only threaten agriculture but cause redistribution of salinity-affected areas. In the dry regions of central Haryana, the primary dependence on groundwater for irrigation has degraded soils through the deteriorating physical and chemical properties of soils coupled with fine-textured Ghaggar alluvium that caused a congenial environment (waterlogging) unfavorable for sustainable agriculture. A thorough investigation of soil and water and spatial distribution of salt-affected soils using remote sensing data are required for precise assessment. The variable extents of salty soils (454–232,000 ha) in Haryana (Abrol and Bhumbla 1971; NRSA 2008) and the complex nature for salts, soil physical properties, and drainage (Sharma et al. 2011; Chinchmalatpure et al. 2016) have been reported periodically. The complex pedogenic processes due to the anthropogenic activities using poor-quality groundwater for irrigation were also reported in arid and semiarid areas (Jain and Kumar 2007; Bhalla et al. 2011). For accurate assessment of reclamation and management, precise diagnosis, quantitative analysis for physicochemical characteristics, and quality appraisal of irrigation water are of primary importance. This chapter addresses role of remote sensing for developing methodology for mapping and chemical characterization of salt-affected soils and quality appraisal of groundwater in Haryana, India, for reclamation and management.

4.7.2 Study Area

The Haryana state (4410 sq.km) lies between 27°39′N 74°27′E and 30°55′N 77°36′E, under the alluvial and aeolian plains, Siwalik and Aravalli hills, that covered 4 agro-eco-regions, 4 subregions, 8 agro-ecological zones and 22 administrative districts. The climate varies from arid to semiarid and subhumid. The average rainfall of the state is 500–600 mm which ranges between 300 and 500 (hot arid region), 50 and 750 mm (hot semiarid region), and 75 and 1050 mm (hot subhumid region). The cultivable area covers 85% of TGA, the area under forest is 168,000 ha (3.8%), and barren and uncultivable land covers 104,000 ha (2.4%). The net irrigated area is 2,532,000 ha (71%) mainly by canals (49%) and groundwater (50%). The primary source of irrigation is Western Yamuna and Bhakra canals. The primary crops include paddy in summer (*Kharif*) and wheat in winter (*Rabi*) seasons, while cotton, pearl millet, sugarcane, sunflower, and pulses (moong) are also practiced. Growing Dhaincha (*Sesbania aculeata*) is common practice in areas under salt-affected (alkaline) soils and water to reduce salt injuries and improve soil health (physical properties). The primary landform is alluvial (Ghaggar and Yamuna alluvium) in general.

4.7.3 Satellite and Related Data Used

Indian Remote Sensing (IRS) (Resource SAT) LISS III data with spatial resolution of 23.5 m and spectral resolution (green, 0.52–0.59 μm; red, 0.62–0.68 μm; near infrared, 0.77–0.86 μm; and short-wave infrared, 1.55–1.70 μm) for March, May, and October 2009–2012 was used in the study (Table 4.1).

The Survey of India topographical maps on 1:50,000 scales were used for preparing the base map comprising of administrative and political boundaries, irrigation/drainage, infrastructure, and settlement. Software ERDAS IMAGINE and ILWIS (*ver 3.3*) were used for digital and spatial data analysis. The software Arc GIS (ver 9.3) was used for generation of thematic layers. A Cal Comp (A_0) digitizer, a scanner, and a printer attached to a Pentium (PIV) computer equipped with Microsoft Windows XP and Office (2000) were used for entry, editing, and

Table 4.1 Particulars of satellite imageries

Sensor	Spectral resolution (μm)	Spatial resolution	Period
IRS- P6 LISS III Resource SAT I	B1 0.52–0.59 (green)	23.5 m	February–March 2009–2010
	B2 0.62–0.68 (red)	Swath 140 km	May–June, 2010–2012
	B3 0.77–0.86 (NIR)		October–November, 2010–2011
	B4 1.55–1.70 (SWIR)		

analysis of map and attribute data. The ancillary data (State Department of Agriculture Haryana and NBSS&LUP, RC Delhi), water quality data (Gupta 2010; Manchanda 1976; HSMITC 2001), crops, and associated land characteristics (District Gazettes Haryana) were also collected for the study area. The salt-affected soil map of Haryana (NRSA 1997) on 1:250,000 was also used as legacy data. Soil sampling tools, like color chart, auger, spade and knife, etc., also were used. Global Positioning System (GPS) was used for collecting data related to the location of field data.

4.7.4 Methodology

4.7.4.1 Geo-Referencing and Digitization for Base Map Preparation Using GIS

The Survey of India (Government of India) topographical maps on 1:50,000 scale were used for geo-referencing and related with real-world coordinates using Universal Transverse Mercator (UTM) projection with projection (ellipsoid WGS 84) and datum (WGS 1984) information. The spatial features for state, district boundaries, roads and railways, canal and river and state, district HQ, and villages were digitized, and the thematic layers were overlaid to develop a base map of the study area.

4.7.4.2 Image Processing and Interpretation of IRS Data

The IRS imageries were processed for radiometric and geometric corrections and were geo-referenced. The False Color Composites (FCC) were prepared using combination of bands such as NIR, R, and G (B321) and SWIR, NIR, and R (B432). The seasonal data were also analyzed to study the dynamics of soil salinity and waterlogging. Visual analysis was done, and interpreted units were digitized following standard guidelines (Colwell 1996). The principal component analysis was done to segregate homogenous data for visual analysis, and filters were used to improve sharpness of the images for visual analysis. The spectral response patterns were analyzed for spatial properties of salt-affected, waterlogged, vegetation, crop, and sandy soils. Spectral reflectance was calculated based on the mean reflectance in bands B2, B3, and B4. NDVI [(B3−B2/(B3+B2)] and VI (B3/B2) were used to distinguish normal and stressed crops. Principal component analysis was performed to homogenize digital data and achieve higher accuracy in image classification. An average (AVG 3 × 3) filter was used to enhance image sharpness for visual analysis and reduce noises prior to multiband image classification. The nearest nine pixels were used to assign the values for central pixel to reduce noises and enhanced interpretation of the images. Digital classification was performed using a supervised classification approach based on maximum likelihood classifier. Ground truth, laboratory analysis, and land use data such as field crop, forestry, urban settlement, roads, and natural water for pond, river, and canal were included as training sets for digital classification. Legacy data such as digitized maps of salt-affected soils, water table depth and quality, and the Survey of India maps were used as supporting data (Saxena 2003; Verma et al. 2004). Average reflectance of a cluster of homogenous

Table 4.2 Keys to the degree of salinity/sodicity in salt-affected soils (Richards 1954)

	Saline soil	Sodic soil	
Degree	ECe (dS m^{-1})	pHs	ESP
Slight	4.0–8.0	8.5–9.0	<15
Moderate	8.1–30.0	9.1–9.8	15–40
Strong	>30	>9.8	>40

pixels in B1 to B4 of March season was assigned a class name, and the sample statistics (feature space) of the training set was generated to separate pixel classes assigned as training set and a scatter plot of two bands.

4.7.4.3 Field Survey for Soil Profile and Related Ground Truth Studies

Ground truth studies were conducted to verify and authenticate interpreted units and establish relationship between image interpretation and field conditions. During field survey important properties such as surface salinity and waterlogging status, seasonal behavior, topography, irrigation/drainage, and crops/cropping practices were studied. GPS (Global Positioning System) was used to locate sites for ground truth observations, soil profiles, and soil and water sampling. The groundwater samples were collected from tube wells (used for irrigation in agriculture). The soil profiles (10 Nos.) were studied to a depth of 1.5 m at representative locations, and depth-wise soil samples were collected for laboratory analysis for soil physicochemical properties (Soil Survey Staff 1998). These were classified using taxonomic system of soil classification (Soil Survey Division Staff 2004). The soil samples were also characterized (Richards 1954) for salinity/alkalinity appraisal (Table 4.2).

4.7.4.4 Laboratory Studies for Soil Characterization, Classification, and Water Quality

Soil samples were analyzed for physicochemical properties, viz., pHs; ECe (dS m^{-1}); soluble ions (me L^{-1}) such as Na^+, K^+, Ca^{2+}, Mg^{2+}, CO_3^{2-}, HCO_3^-, and Cl^- (me L^{-1}); $CaCO_3$ (<2 mm size, %) and organic matter (OM%); CEC (cation exchange capacity as c mol (p^+) kg^{-1}) and ESP (exchangeable sodium percentage); sand (%), silt (%), and clay (%); soil texture; and available (AV.) N (nitrogen, kg ha^{-1}), P (phosphorus, kg ha^{-1}), and K (potassium, kg ha^{-1}) (Jackson 1996; Singh et al. 1999). Soils are classified as saline, sodic, and saline-sodic and the degrees of classes as slight, moderate, and strong (Richards 1954). The waterlogged areas were classified as permanent waterlogged (surface ponding) and subsurface waterlogging (water table depth <1.5 m) based on NRSC (2007). Groundwater (GW) samples were collected from tube wells/open dug wells to study the water quality for agricultural applications. These were analyzed for pH_{iw}; EC_{iw} (dS m^{-1}); soluble ions (me L^{-1}) such as Na^+, K^+, Ca^{2+}, Mg^{2+}, CO_3^{2-}, HCO_3^-, and Cl^-; SAR (sodium adsorption ratio) $= [Na^+/\{(Ca^{2+} + Mg^{2+})/2\}^{1/2}]$, and RSC (residual sodium carbonate) $= [(CO_3^{2-} + HCO_3^-)-(Ca^{2+} + Mg^{2+})]$.

4.7.5 Mapping of Salt-affected and Degraded Soils Using GIS

An integrated approach of image interpretation, ground truth survey, and laboratory analysis data for soil physicochemical properties was used for mapping salt-affected and waterlogged soils (NRSA 2007; Mandal and Sharma 2012, 2013; Dwivedi 2001). Overlaying thematic layers of base map and ancillary data, the interpreted units were delineated using on-screen digitization technique. The thematic map of salt-affected soils for Haryana state was prepared. The area statistics of salt-affected and waterlogged soils were generated (Mandal and Sharma 2011a). The thematic layers of salt-affected soils were linked with the physicochemical properties of soils to develop a relational database (Mandal and Sharma 2011b). Supervised classification was carried out using a nearest neighborhood operator. An interactive database was prepared integrating maps prepared from digital and visual analysis, and a confusion (error) matrix was generated for accuracy assessment.

4.8 Visual Interpretation of IRS Data for Degraded Soils

Strongly sodic soils (white to yellowish white tone in B321, irregular shape), normal crops (bright red tone, continuous), and waterlogged soil (surface ponding, dark blue to black tone, irregular shape) were easily detected based on their strong signatures from the visible and infrared bands in the IRS data. Image interpretation identified salt-affected soils as white to yellowish white patches in the old alluvial plains of Ghaggar and Saraswati (Fig. 4.1). Dark blue to black patches and red to dark red tone indicated the association of waterlogging, soil salinity, and patchy cropped areas. FCC of bands B432 (SWIR, NIR, and R) showed higher contrast and clear boundaries of waterlogged areas than the FCC of bands B321 (NIR, R, and G). Prominent waterlogging and salt infestation were also located in the old paleochannels of Saraswati in Kaithal district. The ground truth data indicated that prolonged irrigation with salty groundwater caused low permeability, infiltration, and poor drainage in moderate- to fine-textured soils at subsurface depths in Ghaggar plain. Barren patches interspersed with cropped areas showed the existence of waterlogged soils and poor vegetative growth in Siwan block. The ground truth data confirmed the presence of sodic soil and the practice of poor-quality groundwater for irrigation in wheat and rice crops. IRS imagery also indicated prominent waterlogging, severely salt-affected soils, and the absence of natural drainage. Ground truth studies indicated the presence of fine-textured layers at subsurface depth inhibiting percolation of salts, water, nutrient, and restricted root growth. At places, salt crusts and sodic groundwater were detected in the forest-covered areas near Pehowa in Saraswati forest range of Kurukshetra district. The spatial distribution of salt-affected soils indicated common occurrence in the Markanda and Ghaggar plains in Ambala district. IRS LISS III March data showed temporary waterlogging and alkali soil formation in the patchy cropped areas. White salt crust along the Bhakra canal command indicated soil salinization.

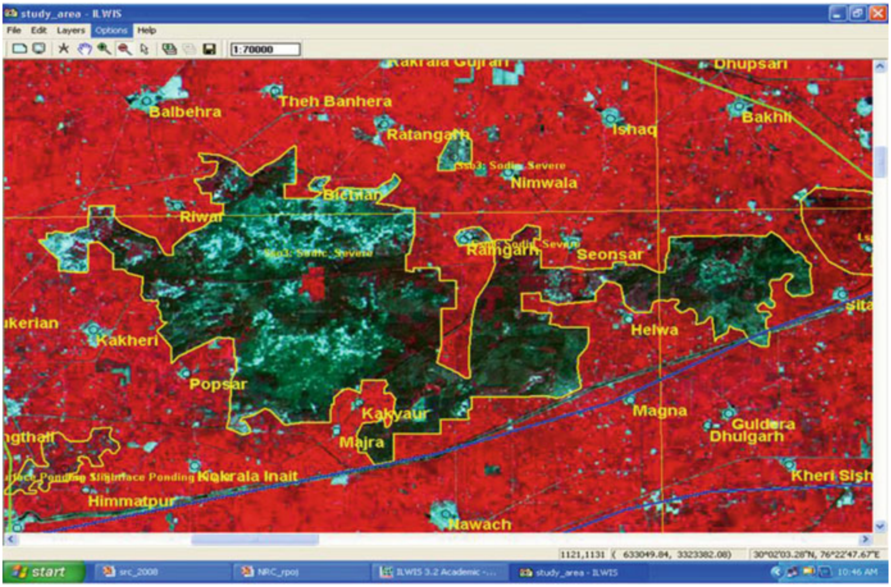


Fig. 4.1 Salt-affected soils viewed in IRS LISS III data

In the irrigated areas, waterlogging and soil salinization were identified in the low-lying flats/depressions with imperfect internal drainage in central Haryana (Fig. 4.2). Continuous irrigation in poorly drained areas caused rise of water table. The salt concentration was higher in post-monsoon season due to salt transport with rising water table. Repeated wet and dry cycles favored salt precipitation and enriched salt concentration during the dry period. Critical areas include the canal commands of WJC and Bhakra that covered Hisar, Jind, Bhiwani, and Sirsa districts. Prominent areas of waterlogging and soil salinization were also identified along the Bhakra canal command in Narnaud, Hansi, Hisar, Barwala, and Uklana blocks, Hisar district.

The periodic use of the saline groundwater for agriculture increased salt concentration in soil profile that deteriorated soil physical properties and favored waterlogging at the low-lying areas. IRS data (2009) showed mixed spectral signatures of dry salts and dark tones of residual moisture at the soil surface that indicated signatures of sodic soils and temporary waterlogging along the paleochannel of river Chautang. In dry areas, the use of sodic groundwater for irrigation favored developing strongly sodic soils appearing as white patches of barren salt crust in Chika block. The moderately sodic soils were appearing as tiny white patches in irrigated areas with good-quality groundwater interspersed with red to dark red tones of crops (Mandal and Sharma 2011a). Partially reclaimed sodic soils showed moderate crop cover and intermittent salt patches in low-lying flats and depressions of Panipat, Karnal, and Kurukshetra districts (Mandal 2012). Slightly sodic soils showed good to very good crop and vegetative covers (Howari 2003),

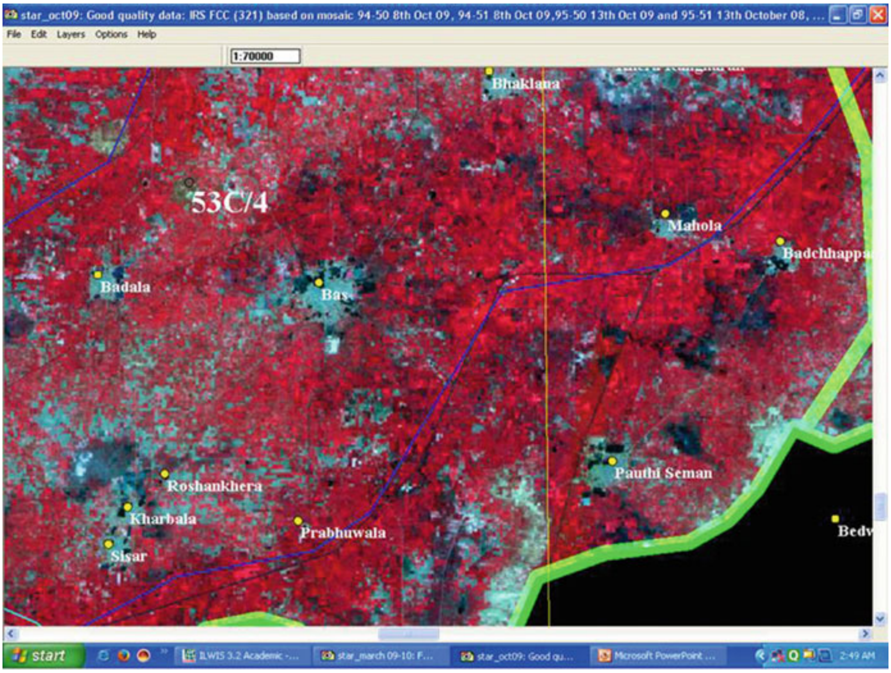
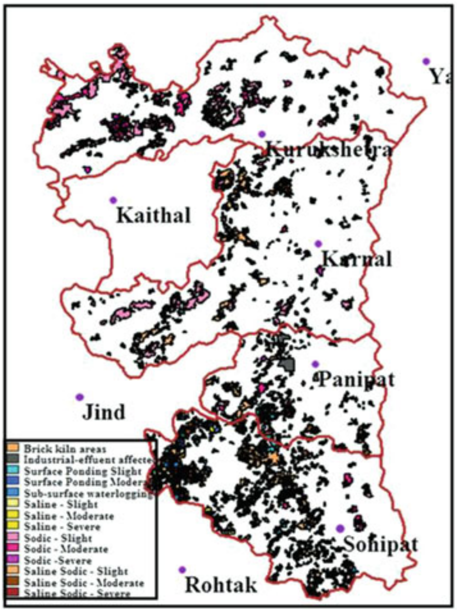
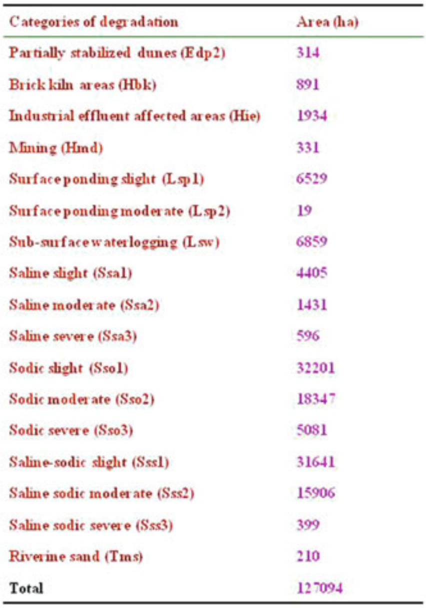


Fig. 4.2 Waterlogging in the irrigated areas of Hisar district

though the field study reported low productivity due to crop damages in the maturity stage. The similarity of spectral signatures for village settlements (muddy roof top) and barren salt-affected soils caused spectral confusion during digital analysis. Visual analysis revealed definite shape and sizes of rural settlements that differ from irregular pattern in salt-affected soils (Khan et al. 2005). Mixed gray to reddish gray and mottled red tones indicated waterlogging in cropped areas (Mandal and Sharma 2013), which was authenticated during field studies. The linear shape of canals and typical curvilinear meandering rivers differs from stagnant water bodies (waterlogged surface) though these elements showed similar spectral reflectance.

Visual analysis of IRS LISS III data (2005–2006) revealed the distribution of salt-affected soils (saline, Ssa; sodic, Sso; and saline-sodic, Sss), subsurface waterlogging (Lsw), surface ponding (slight, Lsp1, and moderate, Lsp2), brick kiln (Hbk), industrial effluent affected area (Hie), partially stabilized dune (Edp2), riverine sand (Tms), and sand mining (Hmd) in Karnal, Kurukshetra, Panipat, and Sonepat of central Haryana. The salt-affected areas were identified as with high surface reflectance of dry salts during summer season and as small patches amidst the cropped areas with poor crop stand and vegetative growth. In the forest areas, these soils were identified in February–March season due to lesser vegetative coverage following litter fall. Ground truth studies revealed localized patches of moderately to severely salt-affected soils with variable extent in Panipat and Kurukshetra districts. Prominent waterlogging was found in irrigation command





Categories of degradation	Area (ha)
Partially stabilized dunes (Edp2)	314
Brick kiln areas (Hbk)	891
Industrial effluent affected areas (Hie)	1934
Mining (Hmd)	331
Surface ponding slight (Lsp1)	6529
Surface ponding moderate (Lsp2)	19
Sub-surface waterlogging (Lsw)	6859
Saline slight (Ssa1)	4405
Saline moderate (Ssa2)	1431
Saline severe (Ssa3)	596
Sodic slight (Sso1)	32201
Sodic moderate (Sso2)	18347
Sodic severe (Sso3)	5081
Saline-sodic slight (Sss1)	31641
Saline sodic moderate (Sss2)	15906
Saline sodic severe (Sss3)	399
Riverine sand (Trns)	210
Total	127094

Fig. 4.3 Mapping and assessment of land degradations in Central Haryana

areas of Sonepat district. High water table (<1.5 m) depth has favored salt accumulation at surface during the dry seasons. Prominent waterlogged soils were identified in the irrigated areas of Gohana block in Sonepat district (Fig. 4.3).

Soil profile studies revealed the distribution of salt-affected soils in the Ghaggar flood plain of Kurukshetra district. Satellite imageries also showed waterlogging due to the irrigation with poor-quality groundwater. Severely salt-affected soils were identified in Saraswati forest range under Pehwa block and Seonti forest area under Ladwa block of Kurukshetra district. The chemical analysis data of soil profiles showed sodicity to the extent of pH 11 at surface in Saraswati and pH 10.2 below the surface in Seonti RF. Salt-affected soils were identified in the Markanda flood plain with moderate crop stand (Fig. 4.4).

The satellite imageries showed soil salinization in the paleo-channels of river Chautang affecting large areas of rice-wheat crops. Chemical analysis of soil and groundwater quality showed high salt load in water samples and slight to moderate alkalinity and fine-textured strata in soil profiles. Patchy salt-affected soils were found in Rajaund and sporadic sodic soils in the Nilokheri and Indri blocks, and slightly to moderately sodic soils were located near the Chautang escape that drained alkaline salts from the Siwalik regions.

Salinity and sodicity were located in Israna block of Panipat district, where significant areas (23,030 ha) of salt-affected soils (Fig. 4.5) were reclaimed and further used for rice-wheat production. Severely sodic soils were used for thermal power and fertilizer production and oil refinery projects. Following successful

Fig. 4.4 Strongly sodic soils in Saraswati forest range of Kurukshetra district

Fig. 4.5 A barren sodic soil (pHs > 10) in Village Naultha District Panipat

Fig. 4.6 Prosopis – a common vegetation in barren salt-affected soil

reclamation, moderately to highly sodic soils were used for crop production and at places used for grazing purposes (Fig. 4.6).

Prominent areas of saline and sodic soils were located Gohana and Kharkhauda blocks of Sonepat district along the Western Yamuna canal command. Large-scale waterlogging and soil salinization rendered vast irrigated areas out of cultivation (Figs. 4.7 and 4.8). Soil profile studies identified fine-textured clayey layer, profuse accumulation of calcium carbonate nodules at the surface horizon, and thick impermeable layer of calcium carbonate concretions that restricted water movement and leaching of salts beyond the root zone (Sharma and Mandal 2006).

4.9 Digital Analyses of Remote Sensing Data for Spectral Properties of Degraded Soils

Spectral analysis of IRS data identified prominent energy absorption for waterlogged area (surface ponding, SP_S) during October (B3 > B4 > B2) and March (B3 > B4 > B2) (Mandal and Sharma 2001). Sodic soils showed higher reflectance (B2 > B3 > B4) in green band (0.55 nm) during June, apparently due to dry and bare soil cover and less vegetation. The reflectance of strongly sodic soils was ~40% higher than the moderately sodic soil (Sehti et al. 2012). The lower reflectance values

Fig. 4.7 Soil salinity affecting productivity in irrigated areas of Gohana, Sonepat district

Fig. 4.8 Surface ponding from canal seepage and poor natural drainage in Sonepat district

of moderately sodic soils in red (650 nm) and SWIR (1625 nm) bands appeared to be due to higher vegetative cover. The reflectance of moderately sodic soil irrigated with good-quality groundwater was ~20% higher than soils irrigated with sodic groundwater during March season (Mandal et al. 2016). The reflectance of strongly sodic soils increased ~40% for irrigating with normal groundwater during October (rice season) and decreased ~60% due to less salt load and low cropping density during June and unchanged with wheat crop that requires low frequency of irrigation water during March (Mandal et al. 2016). The slightly sodic soils with normal groundwater followed an order of B3 > B4 > B2 possibly due to higher canopy cover. The reflectance of surface ponding (SP_S) was low due to higher energy absorption during March (less irrigation) and October (rice crop) seasons and minimum during June (dry season). The reflectance of subsurface waterlogged soils (SSW) is ~80% higher in B3 (NIR) than B4 (SWIR) and B2 (green) as a result of higher crop canopy cover and low due to submergence of water during October (rice crop). The reflectance in NIR band was higher in normal crop due to healthy vegetation. Matured winter crops showed higher reflectance of B3 during March (B3 > B4 > B2), while crops with moist soil surface showed higher values of B4 during October. The spectral reflectance of riverine sand was high (60–100) due to bare surface. The low reflectance values of irrigated sodic soils in March data (40–60) appeared to be due to surface moisture. Similar results were reported for carbonate-rich salts in visible (0.55–0.77 μm) and infrared (0.9–1.3 μm) ranges (Csillag et al. 1993; Rao et al. 1995; Khan et al. 2005).

The NDVI values were low (0.1–0.3) in soils with less vegetative cover (Mandal and Sharma 2011a). Waterlogged soils showed low NDVI values (0.24–0.34) and indicate stressed vegetation (Joshi et al. 2002). Crop irrigated with poor-quality groundwater showed low NDVI values (0.18–0.52), and it increased (0.48–0.52) in areas with normal groundwater. Low NDVI values (−0.04 to 0.04) of riverine sand indicated the scanty vegetative cover. The higher NDVI values of moderately sodic soils (0.29–0.52) may be ascribed to higher vegetative cover and also management interventions at selected locations (Mandal and Sharma 2011a; Raghuwanshi et al. 2010).

The principal component coefficients (PC) showed significant relationship between B1 and PC1 (0.524); B2 and PC4 (0.831); B3 and PC1 (0.707) and PC2 (0.683); and B4 and PC3 (0.670). PC1 showed 93.5% variance, while PC2, 3, and 4 showed 5.91, 0.30, and 0.09%, respectively. The feature spaces for B1 and B2, B1 and B4, and B2 and B4 indicated positive relation and null or partial relation between B1 and B3, B2 and B3, and B3 and B4. An interactive (cross) database was prepared using maps prepared from visual analysis and digital classification. A confusion (error) matrix was prepared to assess the accuracy of digital classification. The data showed an overall accuracy 25.4%, average accuracy 18.0%, and reliability 10.5%, respectively. The slightly sodic soil showed highest accuracy (34%, reliability 65%) followed by subsurface waterlogging (27%, reliability 3%), riverine sand (27%, reliability 21%), and moderately sodic soil (11%, reliability 35%), respectively.

4.10 Soil Physicochemical Properties and Suggested Management Practices

4.10.1 Kaithal District

The physicochemical properties of soils from Kaithal district are presented in Table 4.3. Pedon 1 (P1) showed salt accumulation; sodic condition; moist soil strata; deep, fine soil texture; massive to moderate, fine to medium, angular to subangular blocky structure; and the significant presence of iron and manganese mottles (1–2 mm, 10–20%) at 24–105 cm depth and calcium carbonate concretions (2–4 cm, 20–40%) at 70–135 cm depth, respectively. Based on the data of physicochemical properties (pHs 10.3–10.4 and ESP 75.4–83.2), the Pedon is classified as strongly sodic (Richards 1954). The higher contents of CO_3^{2-} + HCO_3^{-} (14.5–16.9 me L^{-1}), Na^+ (15.6–44.9 me L^{-1}), Cl^- (8.0–14.0 me L^{-1}), and SO_4^{2-} (2.8–7.0 me L^{-1}) ions were noted. The soil texture ranges from silty clay loam to loam showing higher clay content (12.2–36.6%). CEC varies from 28.7 (at surface) to 13.6 (at 187 cm) c mol (p^+) kg^{-1}. The *calcrete*s ($CaCO_3$) are present (10.2–11.4%) at 1m depth. The organic carbon, available nitrogen, and phosphorus contents are low throughout. These soils can be used for rice-wheat cropping following reclamation with gypsum (4–6 Mg ha^{-1}).

Located at the old alluvial plain of Ghaggar (Sachdev et al. 1995; Mandal 2014) and irrigated by salty groundwater (Kaithal block), Pedon 2 (P2) showed water stagnation and patchy crop stand in March and November satellite data. The soil is characterized by deep, massive to medium, subangular blocky structure, clayey texture, and pale yellow to dark yellowish brown color. The moist to wet subsurface layers and the presence of iron and manganese nodules showed anaerobic condition in soil profile. The physicochemical analysis data indicated both sodic (pH 8.7) and saline (ECe 6.5–8.6 dS m^{-1}) conditions at subsurface depths. The Na^+ (1.5–63.5 me L^{-1}), Ca^{2+}+Mg^{2+} (4–38 me L^{-1}), Cl^- (128–725 me L^{-1}), and SO_4^{2-} (5.9–54.0 me L^{-1}) ions are prevalent. The higher CEC values (42.6–44.1 cmol (p^+) kg^{-1}) arise from high clay content (53–57%) which is also causing poor internal drainage (Mandal 2014; Mandal and Sharma 1997). The soil is low in organic carbon (0.2–0.3%), available nitrogen (11–78 kg ha^{-1}), and phosphorus (16–53 kg ha^{-1}) contents and showed moderate to high available potassium (466–509 kg ha^{-1}). The treatment with FYM or compost is required to improve soil physical properties and internal drainage. The alkali groundwater may be treated suitably with gypsum, while the saline groundwater may be used in mixing or cyclic mode for irrigation purpose (Gupta 2010; Singh 2009).

The subangular blocky structure, silty loam texture, and pale yellow to yellowish red color and sodic groundwater were characteristic features of Pedon 3 (P3) (Jain and Kumar 2007). The scattered crop and higher water absorption (dark gray tone) for waterlogging are typical surface features in the satellite imageries. The pH (8.6–9.3) and ESP (44.6–54.4) values indicated slight to moderate sodicity and are used for rice-wheat cropping following reclamation (0–30 cm). Prominent waterlogging appeared due to fine soil texture (silt loam) and stratification caused

Table 4.3 Physicochemical properties of selected soil profiles from Kaithal district

Horizon	Depth (m)	pHs	ECe (dS m^{-1})	Na^+ (me L^{-1})	Ca^{2+} + Mg^{2+} (me L^{-1})	CO_3^{2-} + HCO_3^- (me L^{-1})	Cl^- (me L^{-1})	SO_4^{2-} (me L^{-1})	OC (%)	ESP	$CaCO_3$ (%)	CEC (c mol (p^+) kg^{-1})	Texture	Clay (%)	Silt (%)	Sand (%)	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
P1:29°47′38.9″N to 76°39′52.3″E Fine-Loamy Sodic Haplustepts, sodic soil in paleo-channel of the river Chautang, calcareous parent material																			
A1	0.0–0.2	10.3	1.6	15.6	4	15.6	8.0	2.8	0.2	76.6	1.9	24.6	sicl	36.6	38.9	24.4	31	17	208
Bw1	0.2–0.4	10.4	2.6	27.4	4	15.1	10.0	5.4	0.2	75.4	1.9	28.7	sicl	34.6	37.4	27.9	27	14	208
Bw2	0.4–0.7	10.3	2.3	22.9	4	14.5	10.0	4.2	0.2	83.2	1.2	25.4	sicl	28.0	32.1	39.8	23	10	188
B21k	0.7–1.0	10.4	3.4	28.7	4	16.7	14.0	5.7	0.2	74.8	2.3	21.1	l	18.3	24.1	57.5	23	10	151
B22k	1.0–1.3	10.4	4.0	44.9	4	16.9	13.0	7.0	0.1	80.1	11.4	14.6	l	12.3	17.6	70.0	19	10	88
BC k	1.3–1.9	10.4	3.6	39.4	4	15.2	14.0	6.4	0.1	82.4	10.2	13.6	l	12.2	16.8	71.0	19	10	93
P2: 29°46′38.9″N to 76°29′–34.9″E Fine Typic Ustochrepts, waterlogged soil, rice basmati (CSR 30) irrigated by sodic water produce moderate yield																			
Ap	0.0–0.2	8.7	1.0	1.5	4	4.0	6.0	5.9	0.3	22.5	1.3	42.6	c	53.2	21.5	25.2	11	21	509
Bw1	0.2–0.6	8.0	6.5	49.5	20	4.5	9.0	41.8	0.3	27.2	0.7	44.1	c	55.6	23.2	21.1	78	16	488
Bw2	0.6–0.9	8.0	8.6	63.5	38	3.5	12.0	54.0	0.2	31.3	1.2	44.1	c	57.3	22.3	20.4	74	53	477
Bw3	0.9–1.2	7.9	8.0	44.2	24	4.5	19.0	44.2	0.2	21.8	1.3	42.6	c	57.6	23.6	18.8	70	39	466
P3: 29°46′46.4″N to 76°30′1.9″E Fine-Loamy Typic Ustochrepts, sodic soil and sodic GW, calcareous parent material, rice CSR 30 grown, low yield																			
Ap	0.0–0.2	8.6	2.5	22.3	6	4.5	10.0	13.6	0.3	44.6	3.2	13.2	sil	21.4	28.0	50.5	10	38	456
Bw1	0.2–0.6	9.2	1.2	12.4	6	4.0	8.0	5.9	0.1	52.3	3.8	19.7	sil	24.8	32.7	42.3	51	34	429
Bw2	0.6–0.9	9.2	1.7	19.4	4	4.5	8.0	8.8	0.1	45.8	1.5	22.6	sil	23.6	38.1	38.2	43	23	413
Ck	0.9–1.2	9.3	1.9	21.2	6	4.5	8.0	10.9	0.1	54.4	9.9	26.9	sil	19.6	29.3	51.0	31	13	360
P4: 29°49′6.7″N to 76°28′10.6″E Fine Typic Ustochrepts, sodic soil and sodic GW in the old Ghaggar plain, severely waterlogged and partially barren																			
A1	0.0–0.2	8.3	2.3	18.8	8	1.5	10.0	13.7	0.4	32.3	2.3	21.5	c	40.0	24.1	35.8	10	33	392
Bw1	0.2–0.6	8.6	2.4	17.7	8	3.0	6.0	11.9	0.2	40.1	1.4	26.8	c	47.0	24.2	28.7	70	22	356
Bw2	0.6–0.9	8.4	2.5	19.9	8	4.0	8.0	16.5	0.2	37.3	1.7	31.8	c	49.8	25.4	24.7	70	12	339
Bw3	0.9–1.3	8.0	4.1	35.5	10	5.0	10.0	28.3	0.1	29.7	2.1	36.0	c	54.1	25.6	20.3	51	14	332
P5: 30°3′39″N to 76°18′33.9″E, Loamy Sodic Haplustepts, severely sodic soil and GW in the recent Ghaggar plain, barren with sparse vegetation																			
A1	0.0–0.2	9.9	6.1	64.5	1.5	6.5	23.0	33.9	0.2	56.0	2.1	16.4	l	14	17.8	68.6	88	28	377
B1	0.2–0.6	10.4	8.9	108	1.5	9.0	29.0	52.8	0.2	61.0	1.8	19.5	l	14	22.0	65.8	19	28	470
B2	0.6–0.8	10.6	5.8	56.7	1.5	8.5	16.0	38.4	0.1	60.0	3.0	20.0	l	18	22.1	59.3	15	19	203
Ck	0.8–1.2	10.7	5.0	42.3	2.0	17.5	14.0	16.5	0.1	64.0	2.9	19.5	l	21	19.6	59.1	15	25	203
P6: 30°8′56.3″N to 76°24′37.2″E, Fine-Loamy Typic Natrustalf, reclaimed sodic soil, calcareous, rice-wheat grown, and produce moderate yield																			
A1	0.0–0.2	9.1	1.2	13.3	2	5.0	5.0	4.4	0.6	53.1	4.4	19.2	sil	25	28.1	47.1	86	14	321
Bt1	0.2–0.5	9.6	1.4	15.7	1	6.0	4.0	9.6	0.2	66.7	8.1	16.8	sicl	37	24.8	38.5	27	24	349
Bt2	0.5–0.9	9.7	1.6	18.5	1	7.0	4.5	9.2	0.1	69.0	5.2	20.0	sicl	29	33.3	38.0	14	27	488
Ck	0.9–1.2	9.6	1.7	19.5	3	6.0	3.0	8.4	0.2	58.5	9.5	21.2	sil	25	39.7	35.9	14	26	396

(continued)

Table 4.3 (continued)

Horizon	Depth (m)	pHs	ECe (dS m^{-1})	Na^+ (me L^{-1})	Ca^{2+} + Mg^{2+} (me L^{-1})	CO_3^{2-} + HCO_3^- (me L^{-1})	Cl^- (me L^{-1})	SO_4^{2-} (me L^{-1})	OC (%)	ESP	$CaCO_3$ (%)	CEC (c mol (p^+) kg^{-1})	Texture	Clay (%)	Silt (%)	Sand (%)	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
P7: 30°2′36.3″N to 76°14′49.5″E Loamy Typic Ustochrepts, sodic soil in recent alluvial plain, calcareous, rice-wheat crops showed moderate yield																			
Ap	0.0–0.2	8.9	4.4	39.2	4	5.3	12.5	22.4	0.4	40.0	2.3	24.5	l	23	21.6	55.0	82	10	243
Bw1	0.2–0.6	9.0	4.8	42.3	2	4.0	17.5	28.4	0.2	38.1	2.6	21.1	l	15	17.4	67.4	23	9	286
Bw2	0.6–0.9	9.1	3.6	34.1	4	4.8	15.0	17.9	0.2	46.6	2.3	16.3	l	15	18.1	66.6	20	14	340
Bw3	0.9–1.2	9.4	2.4	19.2	2	3.5	10.0	8.8	0.1	44.2	4.1	19.0	sil	19	31.6	49.9	16	18	303
P8: 29°59′54.3″N to 76°25′41.3″E Fine-Loamy Typic Natrustalf, strongly sodic soil in old alluvial plain, natural vegetation and forestry plantations																			
A1	0.0–0.2	10.6	7.4	98.7	4	15.0	31.0	10.9	0.1	99.5	2.4	14.3	l	15.2	14.7	69.9	79	56	543
Bt1	0.2–0.6	11.0	5.5	80.0	4	15.0	18.0	12.8	0.1	91.8	2.4	20.6	cl	24.9	19.4	55.5	73	43	490
Bt2	0.6–0.9	11.1	4.6	70.4	3	20.0	15.0	9.1	0.1	96.9	0.9	25.7	cl	25.8	18.8	55.2	67	24	463
BC	0.9–1.2	11.2	5.3	83.9	3	27.0	12.0	6.2	0.1	94.1	1.4	24.6	cl	23.3	18.5	58.1	56	15	390
P9: 29°40′35.9″N to 76°13′8.5″E Coarse-Loamy Typic Ustochrepts (Saline phase), waterlogged (WT <0.5m) soil under canal irrigation, cotton crop																			
A1	0.0–0.2	7.9	21.7	168	78	3.0	112	131	0.3	51.5	0.6	14.6	sl	14.7	16.5	68.6	121	25	437
Bw1	0.2–0.5	7.8	19.3	144	74	3.5	104	111	0.2	32.6	0.2	13.6	sl	15.8	15.6	68.5	109	15	389
Bw2	0.5–0.9	7.9	16.7	123	60	3.0	90	90	0.1	43.8	0.5	17.1	sl	19.1	18.7	62.0	90	13	320
B k	0.9–1.3	7.9	12.5	88	48	2.5	80	53	0.1	37.3	10.0	14.1	sl	11.8	23.3	64.8	82	10	277
P10: 29°52′25.3″N to 76°19′49.9″E Loamy Sodic Haplustepts, reclaimed sodic soil in the old alluvial plain, medicinal and aromatic plants growing																			
A1	0.0–0.3	9.6	9.2	117	4.0	20.0	33.0	0.6	0.1	75.9	0.1	13.6	l	13.8	21.8	64.7	115	10	425
B1k	0.3–0.6	10.4	13.7	193	4.0	44.5	32.0	4.6	0.1	91.2	0.6	14.3	l	14.1	24.7	61.1	105	6	358
B2k	0.6–0.9	10.8	13.4	193	3.0	33.0	35.0	8.1	0.1	92.3	0.7	16.6	sil	12.2	26.5	61.2	25	7	268
B3k	0.9–1.3	10.8	11.5	151	3.0	30.0	31.0	7.1	0.1	96.7	0.8	15.0	sil	11.7	25.1	63.1	20	15	186

l loam, *sl* sandy loam, *cl* clay loam, *sil* silt loam, *sicl* silty clay loam, *scl* sandy clay loam due to irrigation by poor-quality groundwater. The Na^+ (12.4–22.3 me L^{-1}), CO_3^{2-}, and HCO_3^- (4.0–4.5 me L^{-1}) ions are dominating and favored sodicity development. The presence of Cl^- (8.0–10.0 me L^{-1}) and SO_4^{2-} (5.9–13.6 me L^{-1}) ions showed the presence of mixed parent materials (Sachdev et al. 1995). The $CaCO_3$ content (1.5–9.9%) indicated calcareous parent materials. The high CEC values (13.2–26.9 c.mol (p^+) kg^{-1}) appeared due to higher clay contents (19.6–24.8%). The organic carbon (0.1–0.3%), available nitrogen (10–51 kg ha^{-1}), and phosphorus (13–38 kg ha^{-1}) contents are low. The gypsum and FYM application is suggested prior to arable cropping.

The pH (8.0–8.6) and ESP values (29.7–40.1) of Pedon 4 (P4) indicated the initiation of sodicity development. The $CaCO_3$ (<2 mm) is evenly distributed (1.4–2.3%) in the soil profile, and higher values may be attributed to the carbonate containing irrigation water. The increase of ECe values (2.3–4.1 dS m^{-1}) at subsurface depths indicated the presence of salty groundwater. The Na^+ (17.7–35.5 me L^{-1}), Ca^{2+} + Mg^{2+} (8.0–10.0 me L^{-1}), CO_3^{2-} + HCO_3^- (1.5–5.0 me L^{-1}), Cl^- (6.0–10.0 me L^{-1}), and SO_4^{2-} (11.9–28.3 me L^{-1}) ions indicated dominance of alkaline parent materials. The higher CEC values (21.5–36.0 c mol (p^+) kg^{-1}) are attributed to high clay content (40.0–54.1%). The increasing ESP values (29.7–40.1) indicated the influence of alkali water for irrigation. The sprinkler and drip methods of irrigation are suggested for irrigation with salty groundwater. The soil is suitable for growing low water-requiring crops, fruits (horticulture), and forestry plantations to sustain in waterlogged soil-affected soils and poor-quality waters.

The pH values (9.9–10.6) of Pedon 5 (P5) indicated strongly sodic soil characterized by sparse vegetation in the Ghaggar plain (Guhla block). The ECe values (8.9–5.0 dS m^{-1}) indicated salt accumulation due to irrigation with salty groundwater (Qureshi et al. 1996). High Na^+ (42.3–108.0 me L^{-1}) and CO_3^{2-} and HCO_3^- (6.5–17.5 me L^{-1}) contents increased soil pHs, and low contents of Ca^{2+} + Mg^{2+} (1.5–2.0 me L^{-1}), Cl^- (14.0–29.0 me L^{-1}), and SO_4^{2-} (16.5–52.8 me L^{-1}) resulted in high SAR. The higher ESP values (56.0–64.0) appeared due to the saturation with Na^+ ions. The low organic carbon (0.1–0.2%), available nitrogen (15–88 kg ha^{-1}), and phosphorous (19–28 kg ha^{-1}) contents indicated low fertility status. For reclamation, gypsum (@ 8–10 Mg ha^{-1}) application is necessary prior to growing arable crop such as rice and wheat.

The Pedon 6 (P6) soil is characterized by silt loam to silty clay loam texture, moderate medium to massive subangular blocky structure, fine consistency, and yellowish brown color. Poor to imperfect drainage and the presence of lime, iron, and manganese nodules and concretions of $CaCO_3$ (calcareous layer) were found at a depth below the surface. The silty clay loam soil texture at subsurface depth with clay content ranging from 29 to 37% and ESP (66.7–69.0%) favored the formation of natric horizon. The pH (9.1–9.7) and ECe (1.2–1.7 dS m^{-1}) values indicated strong sodicity except the surface soil which is reclaimed. Higher contents of Na^+ (13.3–19.5 me L^{-1}), CO_3^{2-}, and HCO_3^- (5.0–7.0 me L^{-1}), as compared to Ca^{2+} + Mg^{2+} (1.0–3.0 me L^{-1}), Cl^- (3.0–5.0 me L^{-1}), and SO_4^{2-} (4.4–9.6 me L^{-1}) indicated strong alkaline ions causing sodicity development. The higher ESP values (53.1–69.0) supplemented soil alkalization. The $CaCO_3$ (<2 mm) content (4.4–9.5%) showed precipitated calcareous parent materials at higher soil pHs and ESP. The Pedon can be used for arable crops following reclamation using gypsum (@ 6–8 Mg ha^{-1}). Due to the presence of *natric* horizon and poor-quality groundwater, plantations of forestry, medicinal, and aromatic plants and low water-requiring food crops are more suitable.

The range of pH and ESP values (8.9–9.4 and 38.1–44.2) of Pedon 7 (P7) indicated moderately sodic soil and higher salt concentration (2.4–4.8 dS m^{-1}) at surface resulting from the irrigation with salty groundwater. The dominance of Na^+ (19.2–42.3 me L^{-1}) and CO_3^{2-}+HCO_3^- (3.5–5.3 me L^{-1}) increased soil pHs. The CEC values (16.3–24.5 c mol (p^+) kg^{-1}) are related to clay content (15–23%). The $CaCO_3$ content is increased with depth (2.3–4.1%). The available nitrogen (16–83 kg ha^{-1}) and phosphorus (9–18 kg ha^{-1}) contents are low. The use of salt-resistant varieties of rice and wheat is suggested to improve productivity.

In the old alluvial plain of Ghaggar (Siwan block), the soil (P8) showed finer soil texture (loam to clay loam), massive to moderate medium subangular to angular blocky structure, yellowish brown to pale yellow color, and poor to imperfect drainage. The pH values (10.6–11.2) showed strongly sodic soil. The high ESP values indicated saturation with sodium favoring hydrolysis and soil alkalinity. The Na^+ (70.4–98.7 me L^{-1}) and CO_3^{2-}+HCO_3^- (15.0–27.0 me L^{-1}) ions are dominating and favored sodicity development (Sharma et al. 2011). The CEC values (14.3–25.7 c mol (p^+) kg^{-1}) showed dominance of mixed mica-type clay minerals. The increasing clay content (24.9–25.8%) and higher ESP (91.8–96.9) showed *natric* horizon formation. The gypsum application @ 8–10 t ha^{-1} is required for reclamation, and the soil can be used for arable (rice-wheat) cropping.

Located in the arid sandy alluvial plain of Ghaggar (Kalayat block) and irrigated with Narwana branch of Western Yamuna canal, Pedon 9 (P9) showed waterlogging (water table depth 0.5m) and poor productivity. A thick layer of $CaCO_3$ concretions (2–5 mm, 50–60%) is found at a depth (120 cm) below the surface. The neutral soil pHs (7.8–7.9) and higher salinity (12.5–21.7 dS m^{-1}) are found throughout the soil profile. The higher contents of Na^+ (88–168.0 me L^{-1}), Ca^{2+} + Mg^{2+} (48–78 me L^{-1}), Cl^- (80–112 me L^{-1}), and SO_4^{2-} (53–131 me L^{-1}) are noted. The $CaCO_3$ (<2 mm) content increased from 0.6 at surface to 10.0% below. The CEC values are low (13.6–17.1 c mol (p^+) kg^{-1}) due to coarse soil texture (sand 62.0–68.8%). The ESP values and the presence of carbonate and bicarbonate salts showed complex saline-alkaline nature. The soil needs installation of subsurface drainage (SSD) to lower the water table depth below the root zone and reduce soil salinity. Alternately it can also be used for aquaculture.

Strongly sodic soil (P10) is located at the old alluvial plain of Ghaggar in central Haryana (Siwan block) and is currently used for forestry, medicinal, and aromatic plantations. The soil texture varies from loam to silty loam, while strong to medium soil structure and pale yellow to dark yellowish brown color at surface and subsurface depths resulted due to high soil sodicity and impaired drainage. The pH and ESP values range from 9.6 to 10.8 and 75.9 to 96.7 at surface and subsurface depths, respectively. The high Na^+ (117.0–193.0 me L^{-1}) and CO_3^{2-}+HCO_3^-

(20.0–44.5 me L^{-1}) contents favored strong sodicity development. The higher soil salinity (9.2–13.7 dS m^{-1}) has resulted from irrigation of salty (high RSC) groundwater. The CEC values are low due to loamy soil texture (sand 61.1–64.7%). The soil needs suitable dosage @10–12 Mg ha^{-1} of gypsum application to neutralize CO_3^{2-}+HCO_3^- and reduce ESP. The arable cropping (rice-wheat) is suggested after reclamation.

4.10.2 Kurukshetra District

Field morphological characteristics of four soil profiles from Kurukshetra district range from deep to very deep, pale brown to dark yellowish brown, sandy loam to sandy clay loam/clay loam texture; medium to strong, coarse to fine angular/subangular blocky structure; sticky, plastic to very sticky, very plastic consistence; presence of few to abundant $CaCO_3$ nodules; and moist to wet subsurface horizons. A few iron and manganese mottles were also found in subsurface (50 cm) layers of P13 (Markanda plain) and P14 (Ghaggar plain), due to prolonged saturation with water. $CaCO_3$ concretions (2–5 cm, 10–30%) were found at 1 m depth in P2 and P4. The textural changes occurred from sandy loam to sandy clay loam and sandy clay loam to clay loam at P11, P12, and P14 apparently due to clay illuviation. The silt and clay contents were higher than sand content in P13 and P14 possibly due to lower topographic position (Table 4.4).

The pH value ranges from 9.1 to 10.7 indicating alkaline reaction. The distribution of ECe values of P11 (4.5–7.4 dS m^{-1}) and P13 (2.4–6.6 dS m^{-1}) indicated moderate soil salinity, while P12 (1.2–8.5 dS m^{-1}) showed higher salinity at subsurface depth, and soil salinity in P14 (1.2–1.8 dS m^{-1}) is low in general. The carbonate plus bicarbonate content is high in P11 (17.0–28.5 me L^{-1}) and P12 (15.7–35.5 me L^{-1}) and low in P13 (5.0–15.5 me L^{-1}) and P14 (5.0–10.0 me L^{-1}). A significant content of $CaCO_3$ (calcretes) was noted at 99 cm and 105 cm depths in P2 (1.3–4.9%) and P4 (4.4–14.5%) which caused restricted drainage and caused low permeability. CEC values were low in P1 (8.8–13.1 c mol (p^+) kg^{-1}) and P13 (13.2–18.4 c mol (p^+) kg^{-1}) due to coarse texture. The higher ESP values in P11 (49.6–76.9), P13 (50.0–94.6), P2 (46.8–56.5), and P14 (53.1–69.0) favored high alkalinity. The higher soil pHs (P3) at 40 cm depth indicated unfavorable soil physical properties and development of waterlogging. The high soil pH of P11 (9.6–10.2) and P12 (9.8–10.7) at surface depth also limits use for arable cropping. The dominance of CO_3^{2-} + HCO_3^- anions and high Na^+ content in P11, P13, P12, and P14 indicated the sodium carbonate and bicarbonate parent materials that favored sodicity development in soils (Bhargava et al. 1980; Sharma et al. 2011). The low contents of Ca^{2+}+Mg^{2+} are due to precipitation of calcium carbonates in an alkaline medium (Bhargava and Bhattacharjee 1982). The texture analysis of P14, P13, P11, and P12 indicated higher clay contents in subsurface layers that caused restricted drainage and favored waterlogging. Higher CEC values in P12 and P14 are attributed due to higher clay content. The high ESP values showed significant saturation with exchangeable Na^+ that favored alkali soil formation. The high

Table 4.4 Physicochemical characteristics of selected soil profiles from Kurukshetra district

Horizon	Depth (m)	pHs	ECe (dS m^{-1})	Na$^+$ (me L^{-1})	K$^+$ (kg ha^{-1})	Ca^{2+} + Mg^{2+} (me L^{-1})	CO$_3^-$ + HCO$_3^-$ (me L^{-1})	Cl$^-$ (me L^{-1})	SAR	OM	CaCO$_3$ (%)	ESP	CEC (c mol (p$^+$) kg^{-1})	Sand (%)	Silt (%)	Clay (%)	Texture
P11 29°59′54.3″N 76°25′41.3″E Strongly sodic soil (Sodic Haplustept) and sodic GW, Ghaggar plain, Kikar, *Prosopis juliflora* plantation																	
A1	0.0–0.1	9.6	7.4	98.7	0.9	4.0	17.0	31.0	49.3	0.08	2.45	49.6	13.1	71.2	14.9	13.7	sl
AB	0.1–0.4	10.0	5.5	80.0	0.2	4.0	21.0	18.0	40.0	0.06	2.45	51.8	8.8	61.9	21.6	16.3	sl
B21t	0.4–0.8	10.1	4.6	70.4	0.1	3.0	28.5	15.0	40.6	0.03	0.98	76.9	11.1	58.8	20.0	21.0	scl
B22t	0.8–1.1	10.2	5.3	83.9	0.1	3.0	27.5	12.0	48.4	0.02	1.47	54.1	13.9	58.6	18.6	22.6	scl
C	1.1–1.4	9.8	4.5	75.8	0.1	3.0	18.5	11.5	43.8	0.02	2.85	43.2	9.5	63.2	20.1	16.7	sl
P12 29°59′02.7″N 76°59′37.6″E Strongly sodic soil, (Sodic Haplustept), good-quality (normal) GW, Yamuna plain, forestry plantations																	
A1	0.0–0.1	9.8	1.2	11.5	0.1	1.0	15.7	3.5	11.5	0.17	1.3	46.8	21.6	59.0	23.0	18.0	sl
B21t	0.1–0.3	10.7	5.3	54.0	0.1	1.5	30.2	12.5	44.1	0.11	1.0	56.5	26.3	53.0	22.0	25.0	scl
B22t	0.3–0.6	10.6	6.2	60.6	0.1	1.0	27.5	10.5	60.6	0.17	2.0	51.8	22.0	52.0	24.0	24.0	scl
B23t	0.6–1.0	10.7	7.6	67.1	0.1	1.0	31.5	12.0	67.1	0.11	3.3	50.0	21.2	52.0	27.0	21.0	scl
Ck	1.0–1.4	10.5	8.5	75.4	0.1	1.0	35.5	12.5	75.4	0.11	4.9	55.0	21.0	53.0	28.5	18.5	sl
P13 30°02′33.6″N 76°51′40.7″E Moderately sodic soil (Sodic Haplustept), cropped (rice), good-quality (normal) GW, Markanda plain																	
Ap	0.0–0.1	9.3	2.4	28.6	0.2	3.0	5.0	25.0	16.5	0.18	5.3	50.0	13.2	51.3	25.1	23.4	scl
AB	0.1–0.4	9.7	2.6	33.0	0.1	2.0	4.0	20.0	23.3	0.08	1.7	94.6	15.5	43.9	31.1	24.8	l
Bw1	0.4–0.8	10.1	4.0	53.9	0.1	2.0	10.0	25.0	38.1	0.08	1.3	94.2	15.9	47.3	26.8	25.8	scl
Bw2	0.8–1.0	10.2	5.9	96.7	0.2	2.0	12.5	30.0	68.3	0.08	1.7	83.1	18.4	48.1	24.7	27.0	scl
Bw3	1.0–1.5	10.0	6.6	99.5	0.2	2.0	15.5	32.0	70.3	0.05	1.9	89.7	16.8	46.2	25.8	28.0	scl
P14 30°08′56.3″N 76°25′37.2″E Strongly sodic soil (Typic Natrustalf), reclaimed at surface, partially cropped, sodic GW, Ghaggar plain																	
Ap	0.0–0.2	9.1	1.2	13.3	0.1	1.5	5.0	5.0	10.8	0.6	4.4	53.1	19.2	47.1	28.1	24.8	scl
AB	0.2–0.4	9.6	1.4	15.7	0.1	1.0	6.0	4.0	15.7	0.2	8.1	66.7	16.8	48.5	24.8	26.7	scl
B21t	0.4–0.7	9.7	1.6	18.5	0.1	1.0	7.0	4.5	18.5	0.1	5.2	69.0	20.0	38.0	23.3	38.8	cl
B22t	0.7–0.15	9.6	1.7	19.5	0.1	2.5	6.0	3.0	12.3	0.2	9.5	58.5	21.2	35.9	29.7	34.5	cl
B23k	1.0–1.6	9.8	1.8	22.0	0.1	4.5	10.0	8.5	10.3	0.1	14.5	65.8	22.0	36.8	35.5	27.7	l

l loam, *sl* sandy loam, *cl* clay loam, *sil* silt loam, *sicl* silty clay loam, *scl* sandy clay loam

Fig. 4.9 Auger-hole technique used for forestry plantation in a sodic soil

$CaCO_3$ contents caused drainage congestion. The soil physical and chemical properties indicated variable alkalinity dominated by alkaline earth metals, and poor drainage caused low permeability (Raghuwanshi et al. 2010). Auger-hole technique devised by CSSRI was successfully used for reclamation of severely sodic soils in Pehowa forest range that support young saplings with adequate amendment and nutrients (Fig. 4.9).

4.10.3 Ambala District

Ground truth studies in Ambala district indicated the presence of sodic soil and concretionary layer of calcium carbonates at subsurface depths that inhibits movement of water. Saline soil was also found along the irrigated areas of Bhakra canal. Significant areas of wastelands were found in the hummocky plain of Naraingarh block. Common source of irrigation is good quality of groundwater. Rice-wheat and oilseed crops are common, and forestry plantation is also practiced along the river course. The results of four representative soil profiles were presented in Table 4.5.

Profiles P15 and P16 were collected from Dangri river plain, and P17 and P18 were located in the Markanda plain. The ranges of pH values (7.9–9.4 in P15, 8.5–9.6 in P16, 9.1–9.5 in P17, and 9.3–9.8 in P18) indicated moderately to strongly

Table 4.5 Physicochemical properties of selected soil profiles from Ambala district in Haryana

Depth (m)	pHs	EC_e (dS m^{-1})	Na^+ (me L^{-1})	K^+ (kg ha^{-1})	Ca^{2+} + Mg^{2+} (me L^{-1})	CO_3^{2-}+ HCO_3^- (me L^{-1})	Cl^- (me L^{-1})	SO_4^{2-} (me L^{-1})	OM	$CaCO_3$ (%)	ESP	CEC (c mol (p^+) kg^{-1})	Texture
P15: Vil. 30°19′56.5″N, 76°57′08.8″E partially cropped													
0.0–0.3	7.9	1.6	12.4	0.05	5	9	12	18	0.33	0.5	24	16	1
0.3–0.6	8.5	1.4	12.9	0.05	7	8	11	20	0.23	1.3	34	21	1
0.6–0.9	9.0	1.4	12.5	0.04	6	10	10	19	0.2	1.1	49	18	1
0.9–0.12	9.4	1.2	11.3	0.04	7	12	10	11	0.21	0.7	60	16	1
P16: Vil. 30°20′43.1″N, 76°57′16.4″E poor crop stand													
0.0–0.3	8.5	1.3	13.0	0.04	8	12	12	14	0.2	1.1	25	11	sl
0.3–0.6	9.2	1.1	10.0	0.03	6	10	13	7	0.2	0.7	54	13	1
0.6–0.9	9.5	1.1	10.0	0.02	7	6	10	7	0.2	0.6	74	14	1
0.9–0.12	9.4	1.1	11.0	0.02	5	4	12	15	0.1	1.8	57	18	cl
P17: Vil. 30°23′10.4″N, 77°02′47.2″E poor crop stand													
0.0–0.3	9.1	1.0	10.0	0.02	7	12	10	5	0.2	1.3	23	15	sl
0.3–0.6	9.2	1.6	15.0	0.04	6	10	9	14	0.2	1.4	28	15	sl
0.6–0.9	9.1	0.9	10.0	0.02	5	10	10	10	0.2	1.5	27	13	sl
0.9–0.12	9.5	0.6	6.0	0.03	4	11	9	–	0.2	1.2	40	14	sl
P18: 30°15′46.0″N, 76°56′01.7″E barren soil													
0.0–0.3	9.8	1.4	14.0	0.12	7	10	10	8	0.1	1.4	39	13	1
0.3–0.6	9.9	1.5	15.0	0.19	6	10	7	4	0.2	1.3	42	14	1
0.6–0.9	9.5	1.8	15.0	0.52	5	8	9	5	0.1	1.2	35	16	1
0.9–0.12	9.4	1.6	14.0	1.74	5	8	8	7	0.2	1.2	22	19	1

sodic soils. Low pHs at the surface layers in P15 and P16 indicated reclamation. pH values increased at the lower depths of P15, P16, and P17 and were consistent at all depths of P18. The dominance of Na^+, Ca^{2+}, Mg^{2+}, CO_3^{2-}, and HCO_3^- salts indicated the presence of alkaline parent materials. $CaCO_3$ content indicated calcareous nature at subsurface depths and imperfect drainage. Low to moderate CEC values are related to coarse to medium soil texture. Particle size analysis data showed loam in P15, loam to clay loam in P16, sandy loam in P17, and loam in P18. P15 showed increasing pHs and ESP (24–60) at subsurface depths and needs careful soil/water management after gypsum application. The pH and ESP (25–75) values of P16 showed sodicity at lower depths. The presence of calcareous layer and higher clay content (13–29%) apparently caused poor drainage and waterlogging. Proper soil and water management is crucial in managing soils after careful reclamation on GR basis. P17 showed higher Na^+, CO_3^{2-}, and HCO_3^- contents that indicated residual sodicity and needs low dosage of gypsum application and is also suitable for growing salt-resistant crops. P18 is a strongly sodic soil located in the Markanda plain, showing high pHs and ESP and loamy soil texture. It needs gypsum application @ 6–8 t ha^{-1} for reclamation followed by salt leaching for arable cropping.

4.10.4 Hisar District

Ground truth studies of Hisar district revealed high water table depth (<1.5 m) causing waterlogging, secondary salinization, and crop damage (Table 4.6). P19 and P20 are irrigated by the Fatehabad branch of Bhakra canal and showed the incidences of waterlogging and high water table depth at 1.5 m depth. It was associated with high soil salinity ranging from 9.8–16.9 dS m^{-1} for P1 and 2.44–12.7 dS m^{-1} for P20. The soil reaction is neutral in P19 (6.4–7.8) and ranges from slightly to moderately alkaline (8.1–9.2) in P20.

Due to high soil salinity, Ca^{2+} and Mg^{2+} contents of P19 (82–127 me L^{-1}) and P20 (7–70 me L^{-1}) exceeded that of Na^+ contents (45.5–103.0 me L^{-1}, 12.52–41.63 me L^{-1}). High Cl^- (70–100 me L^{-1}) and SO_4^{2-} (67.1–86.2 me L^{-1}) contents indicated the presence of neutral salts in P19. The high Na^+ content in P20 was found at higher pH level, and a concomitant decrease of Ca^{2+} and Mg^{2+} contents indicated possibility of precipitation. High SO_4^{2-} contents (141.1–156.9 me L^{-1}) at surface of P20 may be ascribed due to the reclamation with gypsum. The soil pH varies from 8.8 to 9.0 in P21 and 8.7–10.1 in P22 that indicated slight to strong sodicity. The $CaCO_3$ contents increased from 1.4 to 3.6% (P20), 0.3–2.7% (P22), 0.4%–8.96% (P19), and 0.4–24.0% (P21) indicating calcareous nature, indurations, low permeability, and susceptibility to waterlogging. The low CEC values resulted due to coarse to medium soil texture and the presence of non-expanding clay minerals. The ESP values were higher in P20, P21, and P22 due to sodicity. The textural composition showed fine-textured strata in P19 (sandy clay loam) and P20 (loam). The textural changes in P21 (sandy loam to sandy clay loam) and P22 (silty clay loam to clay loam) occurred due to clay illuviation (14–27% in P3, 15–28% in P4).

Table 4.6 Physicochemical properties of soils from Hisar district in Haryana

Depth (m)	pHs	ECe (dS m^{-1})	Na^+ (me L^{-1})	K^+ (kg ha^{-1})	Ca^{2+}+ Mg^{2+} (me L^{-1})	Cl^- (me L^{-1})	$SO_4{}^{2-}$ (me L^{-1})	OM	$CaCO_3$ (%)	ESP	CEC (c mol (p^+) kg^{-1})
P19: 29°10′20.5″N 76°22′28.1″E Barren, waterlogged (WTD 1.5 m), irrigated											
0.0–0.3	7.8	16.9	103.0	0.14	127	200	74.3	0.3	0.4	15.8	15.5
0.3–0.6	6.4	9.8	47.6	0.13	82	80	86.2	0.2	0.3	10.5	16.2
0.6–0.9	6.5	9.8	45.5	0.09	96	70	67.1	0.2	0.7	12.8	13.5
0.9–0.12	7.1	10.8	49.1	0.05	98	100	80.5	0.2	8.96	12.1	9.9
P20: 29°06′58.8″N 76°17′55.0″E waterlogged (1.5 m), crop damaged, irrigated											
0.0–0.3	8.1	12.7	15.9	0.45	70	62	141.1	0.65	2.2	52.8	7.3
0.3–0.6	8.2	11.6	12.5	0.25	60	55	156.9	0.09	1.4	44.1	9.5
0.6–0.9	8.8	4.19	41.6	0.05	12	16	83.9	0.52	3.6	30.9	10.4
0.9–0.12	9.2	2.44	31.1	0.02	7	10	32.5	0.14	3.3	29.7	12.4
P21: 29°03′32.92″N 76°14′32.6″E waterlogged, crop damage, $CaCO_3$ (1.2 m)											
0.0–0.3	8.8	5.5	27.8	tr	8	33	84.9	0.26	0.4	49.7	10.5
0.3–0.6	9.2	2.7	29.4	tr	5	13	28.9	0.22	1.9	54.8	8.3
0.6–0.9	9.1	1.7	20.0	tr	5	11	31.2	0.26	18.8	31.3	6.9
0.9–0.12	9.0	1.9	19.4	tr	6	10	19.3	0.22	24.0	38.5	9.1
P22: 29°03′43.9″N 76°14′15.1″E Barren, thick $CaCO_3$ (1.2 m)											
0.0–0.3	8.7	25.7	303.0	0.9	38	180	123.0	0.28	0.3	29.3	8.7
0.3–0.6	9.5	17.0	251.0	0.1	8	115	49.2	0.21	1.3	57.2	11.3
0.6–0.9	10.1	10.4	156.0	0.0	10	75	76.5	0.22	2.7	51.5	10.4
0.9–0.12	10.1	7.2	91.7	0.0	9	50	66.6	0.27	2.7	58.7	14.7

Table 4.7 Soil physical properties from Hisar district in Haryana (All values are in percentage)

					Silt + clay (<50μ)		$CaCO_3$ (<2 mm) in WDSS			
Depth (m)	Sand (%)	Silt (%)	Clay (%)	Texture	MC (%)	WDSS (%)	CS (%)	FS (%)	Silt (%)	Clay (%)
P19: 29°10′20.5″N 76°22′28.1″E Barren, Waterlogged, irrigated										
0.0–0.3	49	28	23	Scl	51	42	0.1	0.1	0.1	tr
0.3–0.6	50	28	22	Scl	50	35	0.1	0.1	0.2	tr
0.6–0.9	51	26	23	Scl	49	41	0.2	0.1	0.3	tr
0.9–0.12	56	29	25	Scl	54	41	2.8	1.7	0.5	tr
P20: 29°06′58.8″N 76°17′55.0″E Waterlogged, Rice crop										
0.0–0.3	28	44	22	L	66	48	0.4	0.3	0.2	tr
0.3–0.6	52	33	14	L	47	56	0.6	0.2	0.2	tr
0.6–0.9	50	32	18	L	50	77	1.7	0.3	0.4	tr
0.9–0.12	36	39	24	L	63	80	1.1	0.3	0.7	tr
P21: 29°3′32.92″N76°14′32.6″E Waterlogged, $CaCO_3$										
0.0–0.3	54	31	14	Sl	45	44	0.7	0.1	0.4	tr
0.3–0.6	57	25	19	Sl	44	49	2.7	0.3	0.5	0.3
0.6–0.9	56	20	24	Scl	44	65	2.6	1.3	2.4	1.7
0.9–0.12	47	27	27	Scl	54	62	1.9	3.2	3.6	1.8
P22: 29°03′43.9″N 76°14′15.1″E Barren, thick $CaCO_3$ layer										
0.0–0.3	49	36	15	L	51	50	0.2	0.1	0.4	0.06
0.3–0.6	45	41	15	L	66	54	0.7	0.4	0.4	0.05
0.6–0.9	34	51	16	Sil	77	73	1.6	0.6	6.4	0.17
0.9–0.12	32	40	28	Cl	68	74	0.8	0.5	5.3	0.03

MC mechanical composition, *WDSS* water-dispersible soil separates, *CS* coarse sand, *FS* fine sand

The water-dispersible un-aggregated silt plus clay particles (<50 μ) and $CaCO_3$ contents were studied to assess nature and distribution of natural aggregates and cementation due to carbonates (Table 4.7). The silt plus clay content varies abruptly (35–42%) in P19 and increased in sodic and calcareous soils (P20, P21, and P22). The $CaCO_3$ content is higher in coarse sand (2.8 and 1.1%), fine sand (1.7 and 0.3%), and silt (0.5 and 0.7%) size particles for neutral to alkaline soils (P19 and P20). Significant contents were noted in silt (0.4–3.6%, 0.4–6.4%), fine sand (0.14–3.2%, 0.1–0.6%), coarse sand (0.7–2.7%, 0.2–1.6%), and clay (0.3–1.8%, 0.03–0.17%) particle in moderately to highly sodic soils (P21 and P22). The study revealed that the silt and clay particles (<50 μ size) and concretionary $CaCO_3$ favored formation of stable structures in sodic soils that restricted water movement and favored waterlogging and soil salinization in irrigated areas.

4.10.5 Fatehabad District

The physicochemical characteristics of soil profiles in Fatehabad district were presented in Table 4.8. P23 is located in the Ghaggar plain and showed moderate

Table 4.8 Physicochemical properties of soils from Fatehabad district Haryana

Depth (cm)	pH_s	ECe (dS m^{-1})	Na^+ (me L^{-1})	K^+ (kg ha^{-1})	$Ca^{2+} + Mg^{2+}$ (me L^{-1})	$CO_3^{2} + HCO_3^-$ (me L^{-1})	Cl^- (me L^{-1})	SO_4^{2-} (me L^{-1})	OM	ESP	$CaCO_3$ (%)	CEC (c mol (p^+) kg^{-1})	Texture
P23: 29°32′09.5″N 75°27′51.5″E moderately alkali soil in Ghaggar plain													
0.0–0.3	9.2	2.7	30.1	0.4	4 + 6	3 + 4	10	23.5	0.75	70	2.3	4.5	sl
0.3–0.6	8.9	1.6	28.8	0.1	3 + 5	2 + 9	18	7.9	0.46	62	1.0	4.1	l
0.6–0.9	8.9	1.6	6.01	0.1	5 + 1	4 + 5	20	3.1	0.07	49	2.1	5.9	l
0.9–0.12	9.0	1.1	8.87	0.1	6 + 6	2 + 8	20	0.9	0.07	70	1.2	4.5	l
P24: 29°24′16.7″N 75°18′46.8″E waterlogged (1.5 m), severely saline soil													
0.0–0.3	8.7	46.5	472	8.2	80+120	0 + 20	1210	550	1.36	17	1.1	9.2	ls
0.3–0.6	8.7	11.3	69.7	1.9	40 + 60	0 + 40	510	312	0.64	19	2.4	7.3	sl
0.6–0.9	8.7	11.4	78.4	2.8	40 + 40	0 + 14	268	121	0.52	13	3.0	9.9	sl
0.9–0.12	8.7	10.5	94.0	1.6	42 + 44	0 + 20	900	739	0.87	12	4.9	12.1	sl
P25: 29°38′41.6″N 75°56′03.6″E sodic soil/GW, partial waterlogging, low production													
0.0–0.3	9.0	1.3	18.4	0.09	3 + 3	tr + tr	7	10.0	0.45	28.15	1.8	12.4	scl
0.3–0.6	9.2	1.0	15.8	0.01	3 + 3	2 + tr	4	0.7	0.37	25.48	1.9	16.9	scl
0.6–0.9	9.5	1.6	23.9	0.01	2 + 2	10 + tr	4	0.7	0.18	36.85	0.6	13.8	sl
0.9–0.12	9.4	0.9	13.7	0.02	2 + 2	tr + 2	4	0.5	0.22	20.55	0.5	20.7	sl
P26: 29°38′41.6″N 75°56′03.6″E sodic soil/GW, low productivity, waterlogging													
0.0–0.3	8.8	0.9	13.9	0.04	3 + 7	tr + 5	4	0.6	0.52	13.32	1.9	24.2	sl
0.3–0.6	8.7	0.9	13.3	0.02	tr + 2	tr + 2	3	0.6	0.42	14.81	0.8	26.9	scl
0.6–0.9	8.7	1.6	22.2	0.01	tr + 3	tr + 2	4	2.1	0.27	16.49	0.9	25.8	sl
0.9–0.12	8.8	1.5	21.9	0.02	tr + 5	tr + 2	4	1.2	0.18	14.05	1.4	29.4	scl

alkaline pHs (8.9–9.2). The soluble salt composition showed the dominance of CO_3^{2-}+HCO_3^- (7–11 me L^{-1}) of Na^+ (6.01–30.1 me L^{-1}), and the presence of Ca^{2+}, Mg^{2+}, Cl^-, and SO_4^{2-} was also noted.

The higher ESP values (49–70) indicated saturation with Na^+. The CEC values were low due to the coarse soil texture ranging from sandy loam to loam. P24 is a severely saline soil (ECe 10.5–46.5 dS m^{-1}) irrigated by the Bhakra canal. The salt composition showed the dominance of Na^+ (69.7–472.0 me L^{-1}), Ca^{2+} + Mg^{2+} (80–200 me L^{-1}), Cl^- (268–1210 me L^{-1}), and SO_4^{2-} (121–739 me L^{-1}). The depth-wise $CaCO_3$ content (1.1–4.9%) showed the increasing trend of stratification in soil profile. Soil texture ranges from loamy sand to sandy loam; CEC and ESP values were low to very low. P25 showed alkaline nature (pHs 9.0–9.5) and is irrigated by sodic groundwater showing poor productivity. Na^+ and CO_3^{2-}+HCO_3^- were dominant ions, and the ranges of ESP values (21–37%) indicate slightly to moderately sodic soil. The soil texture is variable ranging from sandy clay loam to sandy loam; higher clay content at surface soil indicated impermeable strata that resulted in temporary waterlogging (shown in the IRS data). P26 showed slightly alkaline nature (pHs 8.7–8.8), and the salt composition is dominated by Na^+ (13.3–22.2 me L^{-1}) and CO_3^{2-}+HCO_3^- (2–10 me L^{-1}). The ESP values were low, and higher CEC values (24–29 c mol (p^+) kg^{-1}) appeared due to fine soil texture, ranging from sandy loam to sandy clay loam. For reclamation and management, P23 needs treatment with gypsum, P2 requires interventions with subsurface drainage, and P25 and P26 should be irrigated with groundwater following treatment by gypsum.

4.11 Water Quality Studies in Haryana

The physicochemical properties of groundwater samples are presented in Tables 4.9, 4.10, and 4.11. The depth of groundwater ranges from 76–83 m in Kaithal, 19–21 m in Kalayat, and 76–91 m in Guhla and Siwan blocks, respectively. The water samples of Kaithal block (PW 1–4) showed neutral to sodic pH_{iw} (7.6–8.3) and dominance of CO_3^{2-}+HCO_3^- (8.5–10.5 me L^{-1}), Na^+ (9.9–17.7 me L^{-1}), and Ca^{2+} + Mg^{2+} (8.0–10.0 me L^{-1}). PW 5 is saline (EC 12.7 dS m^{-1}), showed high SAR (33.6), and showed the dominance of Na^+ (164.8 me L^{-1}), Ca^{2+} + Mg^{2+} (48.0 me L^{-1}), Cl^- (80.0 me L^{-1}), and SO_4^{2-} (54.8 me L^{-1}). PW 6 is sodic (pH 9.3), and high RSC (6.5) resulted due to higher CO_3^{2-} + HCO_3^- (8.5 me L^{-1}) and Na^+ (9.9 me L^{-1}). PW 7–13 showed sodic pH (8.6–9.3), high SAR (5.5–23.4), and at places high RSC (1.0–12.7 me L^{-1}) and is dominated by the Na^+ (6.8–14.1 me L^{-1}) and CO_3^{2-}+HCO_3^- (2.5–15.7 me L^{-1}), Cl^- (1.7–20.0 me L^{-1}), and SO_4^{2-} (0.4–8.8 me L^{-1}) ions. The water samples (PW 7–12) showing low contents of CO_3^{2-}+HCO_3^- and high SAR can be used mixing with good-quality water. PW 6 and 13 should be treated with gypsum for neutralizing residual $NaHCO_3$. PW

Table 4.9 Quality of groundwater samples from Kaithal district

PW	Location and depth (m) of GW	pH_{iw}	EC_{iw} (dS m^{-1})	Na^+ (me L^{-1})	K^+ (kg ha^{-1})	$Ca^{2+} + Mg^{2+}$ (me L^{-1})	$CO_3^{2-} + HCO_3^-$ (me L^{-1})	Cl^- (me L^{-1})	SO_4^{2-} (me L^{-1})	RSC	SAR
Water samples from Kaithal subdivision											
1	29°46′38.2″N 76°30′00.0″E, 76	8.3	1.1	10.3	0.06	10.0	9.0	10.0	tr	tr	4.8
2	29°46′41.8″N 76°30′08.3″E, 83	8.3	1.1	10.3	0.05	10.0	9.5	15.0	tr	tr	4.7
3	29°46′41.3″N 76°29′47.3″E, 76	7.6	1.1	9.9	0.08	8.0	10.5	12.0	tr	tr	4.9
4	29°45′34.1″N 76°24′51.5″E, 76	7.2	2.3	17.7	0.01	10.0	8.5	16.0	7.1	tr	7.9
5	29°41′26.7″N 76°14′4.5″E, 21	7.6	12.7	164.8	0.05	48.0	5.0	80.0	54.8	tr	33.6
6.	29°47′48.2″N 76°27′26.4″E, 83	9.3	1.2	9.9	0.07	2.0	8.5	3.0	tr	6.5	9.9
Water samples from Guhla and Siwan blocks											
7	30°2′29.9″N 76°15′41.6″E, 76	8.6	1.3	10.6	0.1	3.0	2.5	10.0	8.8	tr	8.6
8	30°2′13.3″N 76°14′49.5″E, 76	9.1	1.3	12.6	0.1	1.5	2.5	10.0	6.4	1.0	14.5
9	29°59′36.2″N 76°13′55.5″E, 76	9.3	1.4	14.1	0.1	1.0	3.0	6.0	4.7	2.0	19.9
10	29°59′35.2″N 76°13′41.6″E, 91	9.1	1.2	12.1	0.1	2.0	4.0	20.0	2.9	2.0	12.1
11	30°04′57.5″N 76°20′35.8″E, 91	9.1	1.6	16.6	0.1	1.0	3.0	5.0	7.7	2.0	23.4
12	30°07′08.1″N 76°21′33.5″E, 91	8.8	0.8	6.8	0.1	3.0	2.5	3.0	0.4	tr	5.5
13	29°58′52.7″N 76°29′21.5″E, 83	8.8	1.1	13.9	0.1	2.9	15.7	1.7	tr	12.7	11.5

Table 4.10 Quality of groundwater samples in Kurukshetra district

PW	Water sample- Location and latitude-longitude, depth (m)	pH_{iw}	EC_{iw} ($dS\ m^{-1}$)	Na^+ ($me\ L^{-1}$)	K^+ ($kg\ ha^{-1}$)	$Ca^{2+} + Mg^{2+}$ ($me\ L^{-1}$)	$CO_3{}^{2-}$ ($me\ L^{-1}$)	$HCO_3{}^-$ ($me\ L^{-1}$)	Cl^- ($me\ L^{-1}$)	RSC	SAR
14	29°59′8.4″N 76°25′55.1″E, 108	8.8	1.4	13.9	0.1	2.5	2.0	13.2	1.7	12.7	12.4
15	29°59′54.3″N 76°29′41.3″E, 60	8.7	1.1	9.9	0.2	2.5	1.5	10.0	1.7	9.0	8.9
16	29°59′29.9″N 76°29′39.4″E, 108	9.5	1.4	13.3	0.1	2.0	3.0	11.0	1.7	12.0	13.3
17	30°01′19.9″N 76°27′36.6″E, 100	9.1	1.3	12.6	0.1	1.5	Tr.	2.5	10.0	6.4	14.5
18	29°59′36.4″N 76°29′55.5″E 100	9.3	1.4	14.0	0.1	1.0	Tr.	3.0	6.0	2.0	19.7
19	30°04′57.5″N 76°27′35.8″E, 120	9.1	1.6	16.6	0.1	1.0	0.0	3.0	5.0	2.0	23.4

Table 4.11 Quality of water samples from Fatehabad district

PW	Location, source, and depth (m) of GW	pH	EC (dS m^{-1})	Na^+ (me L^{-1})	K^+ (kg ha^{-1})	Ca^{2+} + Mg^{2+} (me L^{-1})	CO_3^{2-} + HCO_3^- (me L^{-1})	Cl^- (me L^{-1})	SO_4^{2-} (me L^{-1})	RSC	SAR
20	29°38′6.1″N 75°53′7.1″E, 78	8.4	0.8	13.0	0.2	10	10 + tr	18	tr	tr	5.8
21	29°38′41.6″N 75°56′3.6″E, 99	9.7	2.5	36.2	0.4	14	10 + tr	16	tr	tr	13.8
22	29°43′01.3″N 75°47′16.8″E, 85	9.0	0.5	7.08	0.1	10	3 + tr	13	tr	tr	3.2
23	29°38′23.0″N 75°56′08.2″E, 95	9.5	1.8	27.7	0.2	8	10 + 2	10	2	4	13.9

5 showing high SAR may be used alternately with good-quality water. PW 1–4 is suitable for irrigation of salt-resistant varieties.

Chemical properties such as pH (8.7–9.5), RSC (9.0–12.7 me L^{-1}), and SAR (12.4–23.4) of six water samples from Kurukshetra district are presented in Table 4.10. Among the anions CO_3^{2-} (1.5–3.0 me L^{-1}) and HCO_3^- (2.5–13.2 me L^{-1}) and cations Na^+ (9.9–16.6 me L^{-1}) and Ca^{2+}+Mg^{2+} (1.0–2.5 me L^{-1}) and Cl^- (1.7–10.0 me L^{-1}) were dominant. RSC values range from 2.0–12.7 me L^{-1} and are critical in 14 (12.7 me L^{-1}), 16 (12.0 me L^{-1}), 15 (9.0 me L^{-1}), and 17 (6.0 me L^{-1}), respectively (Richards 1954). In general, SAR values are higher (>10). The high pH, RSC, and SAR values of water samples indicated their sodic nature dominated by the presence of CO_3^{2-}, HCO_3^-, and Na^+, while the presence of Ca^{2+} + Mg^{2+} and Cl^- is also noted. Higher SAR values indicated dominance of Na^+ ion, causing soils unsuitable for agriculture (Richards 1954). The critical limits of RSC in 14, 15, 16, and 17 indicated the need for treatment with gypsum for irrigation in field crops. Samples with moderate alkalinity (18 and 19) may be used for the growing salt-resistant varieties.

The chemical properties of four water samples (Table 4.11) from Fatehabad district showed slightly to moderately sodic (pH_{iw} 8.4–9.7) nature; the dominance of Na^+ (7–36 me L^{-1}), CO_3^{2-}, and HCO_3^- (3–12 me L^{-1}); and the presence of Ca^{2+}, Mg^{2+} (8–14 me L^{-1}), and Cl^- (10–18 me L^{-1}). The SAR values showed >10 in Tohana block, while RSC (4 me L^{-1}) was also reported at selected place.

4.12 Assessment and Distribution of Salt-affected Soils

The area under different categories of salt-affected soils was computed based on the statistics derived in GIS (Tables 4.12, 4.13, 4.14, 4.15, and 4.16). Six categories of these soils were identified in Kaithal district distributed in four blocks (Kaithal, Kalayat, Pundri, and Rajaund) pertaining to Kaithal subdivision. In Kaithal block, slightly (4313 ha) and moderately (1809 ha) sodic soils (total 6122 ha) are dominating where sodic groundwater is used for irrigation. Saline soils (804 ha, 0.3%) are also located at selected places confined to the lower topographic zone. Saline (4620 ha, 2%) and sodic soils (1452 ha, 0.6%) are located in the irrigated areas of Kalayat block. Soils are commonly saline (3063 ha, 1.3%) in irrigated areas of Rajaund block. Sodic (4723 ha, 2%) and saline (168 ha, 0.07%) soils are common in Pundri block (4891 ha, 2.1%). Saline (1415 ha, 0.61%) and sodic (1015 ha, 0.44%) soils are common in Guhla and Siwan blocks. In the irrigated areas, slightly saline and sodic soils covered 1415 ha (0.61%) and 1015 ha (0.44%), respectively. In the Ghaggar plain, strongly (143 ha, 0.06%) and moderately sodic (73 ha, 0.03%) soils are commonly found. Strongly sodic (2255 ha, 0.97%) soils are distributed along the paleo-channel of the Saraswati river in Siwan block, while slightly saline (255 ha, 0.1%) and sodic (143 ha, 0.06%) soils are found in the irrigated areas. Thus, salt-affected soils covered 26,301 ha (11.3%) in Kaithal district having sodic and

Table 4.12 Distribution and extent (ha) of salt-affected soils in Kaithal district

Name of the block	Moderately saline	Moderately sodic	Slightly saline	Slightly sodic	Strongly saline	Strongly sodic	Total area	% of TGA
Kaithal subdivision								
Kaithal	148	1809	50	4313	606	tr	6926	3.0
Kalayat	935	1306	1335	146	2350	tr	6072	2.6
Pundri	tr	1682	168	3041	tr	tr	4891	2.1
Rajaund	tr	09	2028	51	1026	tr	3114	1.3
Sub-total	1083	4806	3581	7551	3982	tr	21,002	9.0
Guhla and Siwan blocks								
Guhla	tr	73	1415	1015	tr	143	2646	1.1
Siwan	tr	Tr	255	143	tr	2255	2653	1.1
Sub-total	tr	73	1670	1158	tr	2398	5299	2.3
Grand total	1083	4879	5251	8709	3982	2398	26,301	11.3

TGA total geographical area of Kaithal district

Table 4.13 Extent of salt-affected soils and associated land degradations in Kurukshetra district

Sl No.	Categories of salt-affected soils and associated degradations	Area (ha)	%
1.	Slightly sodic soil	10,409	61.0
2.	Moderately sodic soil	5697	33.6
3.	Strongly sodic soil	34	0.2
4.	Surface ponding-slight	363	2.1
5.	Subsurface waterlogging	203	1.2
6.	Riverine sand	210	1.2
Total		16,916	

saline soils covering an area of 15,986 ha (6.8%) and 10,315 ha (4.4%), respectively. The total affected area was 5064 ha in Ambala district, of which sodic and saline soils covered 4222 ha and 842 ha, while slightly and moderately salt-affected soils covered 4040 and 1024 ha, respectively.

The spatial distribution of salt-affected and waterlogged soils in Kurukshetra showed (Table 4.13) the largest area of slightly sodic soils that covered 10,409 ha (61%), followed by moderately (33.6%) and strongly (0.2%) sodic soils.

The prominent areas of salt-affected soils (11,614 ha, 4.6%) were noted in Fatehabad (1.1%), Tohana (1.1%), and Bhuna (1.3%) blocks in Fatehabad district. Sodic and saline soils covered 7200 ha (62%) and 4414 ha (38%), respectively. Soils are sodic in Tohana (2689 ha, 23%), Fatehabad (2460 ha, 21%), and Bhuna (1216 ha, 11%) and saline in Bhattu Kalan (1976 ha, 17%) blocks, respectively (Table 4.14).

In Jhajjar district, salt-affected soils (41,516 ha) are distributed in four blocks, viz., Bhadurgarh (15,584 ha, 37%), Jhajjar (14,802 ha, 36%), Beri (5973 ha, 14%), and Matenhail (5157 ha, 12%). These are saline (32,731 ha, 78%), sodic (1487 ha, 4%) in general, and complex saline-sodic (7298 ha, 18%) in the irrigated areas (Table 4.15).

The salt-affected soils of Haryana state were compiled and presented in Table 4.16. These soils are distributed in 18 districts, and the largest areas are found in Jhajjar (41,516 ha), Sonepat (35,077 ha), Hisar (34,245 ha), Rohtak (32,633 ha), and Sirsa (30,311 ha). Saline soils are dominant in Jhajjar (33,784 ha), Hisar (33,375 ha), and Rohtak (21,999 ha) districts. Prominent areas of sodic soils are located in Sirsa (30,311 ha) and Sonepat (28,477 ha) districts. The largest areas of sodic soil reclamation occurred in Panipat (27,789 ha, 15%) and Jind (13,271 ha, 7%) districts, while areas of saline soils increased significantly in Hisar (25,605 ha, 52%), Jhajjar (25,427 ha, 51.7%), Rohtak (13,436 ha, 27%), Fatehabad (4414 ha, 9%), and Faridabad (3774 ha, 8%), apparently due to canal irrigation practices in poorly drained areas. Although the areas of sodic soils in Karnal district decreased (10,630 ha, 5.7%), a concomitant increase in sodic areas occurred in Kaithal (3127 ha, 1.7%) and Jhajjar (7115 ha, 4%) districts possibly due to the use of sodic groundwater for irrigation.

Table 4.14 Distribution and extent of salt-affected soils (ha) in Fatehabad district

Name of the block	Moderately saline	Moderately sodic	Slightly saline	Slightly sodic	Strongly saline	Strongly sodic	Total area	% TGA
Ratia	tr	577	tr	238	tr	20	835	0.3
Fatehabad	244	879	120	1334	81	247	2905	1.1
Bhattu Kalan	1099	tr	tr	tr	877	tr	1976	0.8
Bhuna	954	45	664	1171	349	tr	3183	1.3
Tohana	tr	882	26	1807	tr	tr	2715	1.1
Grand total	2297	2383	810	4550	1307	267	11,614	4.6

TGA total geographical area of Fatehabad district

Table 4.15 Extents and distribution of salt-affected soils (ha) in Jhajjar district in Haryana

SN	Name of the block	Saline	Sodic	Saline-sodic	Total (ha)
1	Bahadurgarh	10,058	0	5526	15,584
2	Jhajjar	11,999	1487	1316	14,802
3	Beri	5864	0	109	5973
4	Matenhail	4810	0	347	5157
	Total	32,731	1487	7298	41,516

Table 4.16 Distribution of salt-affected soils (ha) in Haryana (based on IRS data (2010–2013)

SN	Name of the district	Saline	Alkali	Total area
1	Ambala	842	4222	5064
2.	Bhiwani	3005	12,953	15,958
3	Fatehabad	4414	7200	11,614
4	Faridabad	7244	1393	8637
5	Gurgaon	9314	0	9314
6	Hisar	33,375	870	34.245
7	Kaithal	871	9812	10,683
8	Karnal	21	19,162	19,183
9	Kurukshetra	0	15,873	15,873
10	Jind	3170	8635	11,805
11	Jhajjar	33,784	7762	41,546
12	Mewat	7532	1302	8834
13	Panipat	0	7514	7514
14	Palwal	5590	4443	10,033
15	Rewari	7293	0	7293
16	Rohtak	21,999	10,634	32,633
17	Sirsa	0	30,311	30,311
18	Sonepat	6600	28,477	35,077
	Total	145.054	170,563	315,617

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Part II

Drivers, Stressors and Indicators

Salinity Tolerance Indicators

5

Sanjay Arora and J. C. Dagar

Abstract

Soil salinity significantly affects agricultural production and environmental quality. A salinity indicator is that symptom which suggests the impacts of soil salinity. The visual characters serve as diagnostic criteria in identifying the salt-affected soils. The physical indicators of salt-affected soils include flocculation, dispersion of clays and surface salt crusts; and conventional chemical indicators of soil salinity include electrical conductivity (EC), pH, total dissolved solids (TDS), exchangeable sodium percentage (ESP), electrochemical stability index (ESI) and sodium adsorption ratio (SAR). Plant species that serve as indicator species can be commonly used in combination with physical and chemical indicators to determine soil salinity. The relationship between soil electrical conductivity and sodium adsorption ratio serves as an important baseline, with modifications such as soil texture, clay type, leaching fraction and rainfall, for a better site-specific understanding of how plants will be affected by salts and, in particular, sodium. Many plant species, found only grown in highly saline soil (true halophytes) or in tidal zone (mangroves), are the indicators of salinity. So is true with many microbes found in mud flats associated with high salinity in mangal formations. The variation of environmental conditions may influence the behaviours of bioindicators including plants and microbes. Halophyte plant species and halotolerant or halophilic bacteria also serve as viable indicators of salinity as they are adaptive to stress through different mechanisms. This chapter discusses various physical, chemical and biological indicators of soil salinity as well as sodicity, their measurements and impacts.

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Salinity indicators · Halophytes · Halophilic bacteria · Biological indicators · Mangroves

5.1 Introduction

Salt-affected soils occur globally in all the continents and under almost all the climatic conditions. These soils are distributed more extensively in the arid and semiarid regions compared to the humid areas. The nature and properties of these soils are also varied such that they require specific approaches for their reclamation and/or management. Salinization of soil is recognized as one of the most devastating soil degradation threats and has endangered the potential use of soil on almost an estimated global land area of about 1 billion hectares (Table 5.1), representing about 7% of earth's continental extent. It is not only suppressing plant growth but is also disturbing the sustainability of beneficial rhizospheric microorganisms. It has also been estimated that globally, about one-fifth of total cultivated land area is affected by high salinity. The salinized areas are increasing at an alarming annual rate of 10% due to low precipitation, high surface evaporation, weathering of the native rocks, saline water irrigations and poor cultural practices, affecting mainly in the arid and semiarid regions. Also, it is expected that about more than half of the arable lands would turn salinized by 2050 (Jamil et al. 2011).

Soil salinization is a natural or anthropogenic process that causes accumulation of dissolved salts in soil water to such an extent that plant growth is inhibited. The processes of soil salinization may be primary (natural) and secondary (anthropogenic) in nature. These involve accumulation of water-soluble salts, viz. potassium (K^+), magnesium (Mg^{2+}), calcium (Ca^{2+}), chloride (Cl^-), sulphate (SO_4^{2-}), carbonate (CO_3^{2-}), bicarbonate (HCO_3^-) and sodium (Na^+) ions, in the soil. Based on soil type, the extracted solution differs in content of dissolved salts. The salt

Table 5.1 Global distribution of salt-affected soils (Mha)

Regions	Total area (Mha)	Saline soils		Sodic soils	
		Mha	%	Mha	%
Africa	1899	39	2.0	34	1.8
Asia, the Pacific and Australia	3107	195	6.3	249	8.0
Europe	2011	7	0.3	73	3.6
Latin America	2039	61	3.0	51	2.5
Near East	1802	92	5.1	14	0.8
North America	1924	5	0.2	15	0.8
Total	12,781	397	3.1%	434	3.4%

Source: FAO (2008)

concentration in soil, with electrical conductivity (ECs) exceeding 20 mM (~2 dS m^{-1}), is categorized as salt-affected soil (Abrol et al. 1988). A saline soil is thus defined as the soil having a high concentration of soluble salts with EC_e of 4 dS m^{-1} or more that results in inhibiting plant growth. However, many crops are affected by soil with an EC_e less than 4 dS m^{-1}. Excessive content of sodium (Na^+) in soil destroys soil structure, deteriorates soil hydraulic properties, increases soil pH and reduces water infiltration and soil aeration, leading to compaction of soil, accelerating erosion and water runoff. Furthermore, Na^+ being the most prominent destructor of secondary clay minerals by dispersion replaces calcium (Ca^{2+}) and Mg^{2+} and gets adsorbed on the soil surface and/or interlayers of soil aggregates (Ondrasek et al. 2010). The dispersed clay particles undergo leaching through the soil to accumulate and block the pores, especially in fine-textured soils. The soil becomes unsuitable for proper root development and plant growth. The salinity-induced sodicity, where leaching either through natural- or human-induced processes washes the soluble salts into the subsoil and leaves negative charges of sodium bound to the clay, is the secondary result of salinization.

5.2 Soil Salinity Indicators

Soil salinity is one of the important soil properties that significantly affect agriculture crop production and environmental quality. A salinity indicator is a symptom or sign that reflects that the soil is experiencing the salinity impacts. A barren patch in the landscape may indicate a high salt concentration in the soil that inhibits plant growth. However, while interpreting this phenomenon, care should be taken as it might also be because of pedestrian activity that results in compaction of the soil and thus inhibits plant growth. Further investigations are required to determine if the salinity is indeed the cause of any symptom.

The presence of excessive salts on the surface of soil vis-a-vis in the root zone characterizes the saline soils (Fig. 5.1). The major source of the salts in the soil is the primary minerals present in the exposed layer of earth's crust. During chemical

Fig. 5.1 Salts on the soil surface

weathering involving hydrolysis, hydration, solution, oxidation, carbonation and other processes, the salt constituents are slowly released and become soluble. These released salts are transported away from their origin source through surface or groundwater streams. In the groundwater stream, these salts are progressively concentrated as the water with dissolved salts transfers from the more to less humid and relatively arid or dry areas. The dominant ions near the weathering site in the presence of carbon dioxide will be carbonates and hydrogen carbonates of Ca, Mg, K and Na; their concentration, however, may be low. While the water with dissolved solutes moves from the more humid to the arid regions, the soluble salts are concentrated, and the concentration may become sufficiently high resulting in the precipitation of sparingly soluble salts. Apart from the precipitation, the chemical constituents of the water may promote changes through processes of exchange, adsorption, differential mobility, etc., and the resultant of these processes increases the concentration in respect of Cl^- and Na^+ ions in the groundwater and in the soil profiles.

Geologic materials are extremely variable in their elemental composition, and some of the materials are higher in salts. The marine-originated shales can supply appreciable quantities of soluble salts when traversed by water. Consequently, the kind of geologic formations through which the water passes significantly influences the composition and total salt concentration.

Salts that are released through weathering in the dry regions (arid and semiarid areas) receiving limited rainfall are usually deposited at some depth in the soil profile. The depth of the salt deposition depends on factors such as the water retention capacity of the soil; seasonal, annual and maximum rainfall; etc. (Yaalon 1965). If the salts are deposited below 1.5 m or beyond the root zone, they rarely affect the crops adversely unless they are redistributed and accumulate in the surface soil layers.

5.2.1 Physical Indicators

The distinguishing physical characteristics of saline and sodic soils serve as indicators for the nature and the extent of problem through visual diagnosis.

5.2.1.1 Flocculation and Salt Crust

The soil salinity can affect the physical properties of soil as this may cause binding of fine particles into aggregates. This process of aggregation is known as flocculation and is favourable in terms of soil aeration and penetration of roots. Increasing soil solution salinity might have a positive effect on soil aggregation and stabilization but higher levels can cause negative and potentially detrimental effects on plants. Thus, salinity cannot be augmented to maintain soil structure without considering potential impacts on plant health.

Physical indicators of soil salinity include salt crystals and stains of light grey or white colour on surface soils. Excessive salts in saline soil keep the clay in a flocculated state so that these soils generally have good physical properties. The structure of the soil is generally good, and also the tillage characteristics and water permeability in soil are even superior than that in nonsaline soils. When saline soils are leached with low saltwater, these soils tend to disperse, ensuing low permeability to water and air, particularly when the soils are of heavy texture.

5.2.1.2 Other Physical Indicators of Salinity

- *Salinity damage to buildings*

Salinity results in damage of the buildings that may include the crumbling of bricks and mortar, occurrence of white crystals of salt on the exterior and interior wall surfaces, dampness on walls, breakdown of render, bleaching of sandstone and the breakdown of cement.

- *Waterlogging*

Waterlogging causes salinity as water is the medium by which salts move in the landscape. If salt is present in areas of water accumulation, those areas may become more saline as water evaporates leaving salt behind.

- *Barren patches with or without salt crystals*

Bare soil surface sometimes appearing as concentrated salt levels in the landscape may reach a level which adversely affects the vegetation. Even grass does not appear on the surface (see in Fig. 5.1).

- *Soil erosion*

Soil erosion occurs where salinity has resulted in mortality of the protective vegetal cover and the changes to soil structure have made it prone to erosion resulting in increased runoff.

- *"Puffiness" of soil when dry*

Puffiness on the surface of dry soil can be an indication of sodic soil or high content of sodium which is prone to salinity and erosion.

- *Efflorescence*

Efflorescence occurs where crystals of salt form on the surface of soil. These salt crystals can best be seen on a hot dry day when the soil moisture content has evaporated.

- *Clear water in rivers or streams*

Wherever the sediment has dropped out of suspension due to a high salt concentration in the water, the clear water may occur. A salty smell may also be detected.

5.2.1.3 Sodicity and Soil Physical Properties

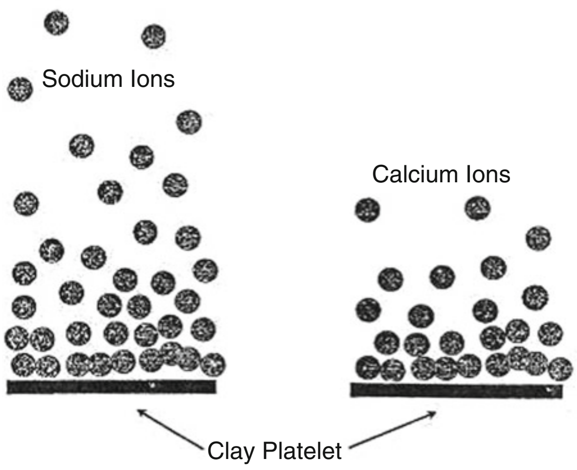
Sodium has the opposite effect of salinity on soils. The primary physical processes associated with high sodium ion concentrations are soil dispersion, clay platelet and aggregate swelling. The forces binding clay particles together get disrupted flanked by too many large sodium ions. When this parting occurs, there is expansion of clay particles causing swelling and soil dispersion.

Dispersion of soil causes clay particles to plug soil pores, thereby reducing soil permeability. On repeated wetting and drying of soil, the clay dispersion occurs, which then reforms and solidifies into almost cement-like soil with little or no proper structure. The three major problems caused by sodium-induced dispersion of soil are reduced infiltration, reduced hydraulic conductivity and soil surface crusting.

Salts of Ca and Mg that contribute to soil salinity do not have this effect because they are smaller and tend to cluster closer to the clay particles (Fig. 5.2). Calcium and magnesium will generally keep soil flocculated because they compete for the similar spaces as sodium on clay particles. Enhanced amounts of calcium and magnesium can reduce the amount of Na-induced dispersion**.**

Appearance of sodic soils in small patches on an area of few square metres may not reflect as separate entities on satellite imageries. Generally, farmers' experience goes a long way in identifying the salt-affected areas, when it is observed that wheat crop is not performing well and also the soil does not support legume crops like cowpea, chickpea, gram, etc. Water stagnation on soil surface for longer time after rains is also experienced by the farmers in sodic soils. This standing water is found to be turbid till it evaporates completely. Soil surface becomes very hard, dense and compact on drying and in some cases develops thin salt layer or crust on the surface or powdery on the surface (reh). Such characteristic on the surface of soil indicates sodic nature of the soil. In severe cases, the soil remains barren. For preliminary *in situ* assessment of sodicity, take a pinch of hand-crushed surface soil in a test tube, and add about 10 ml of distilled water to suspend, and thereafter add few drops of

Fig. 5.2 Behaviour of Na and Ca binding to clay particles. (After Hanson et al. 1999)



phenolphthalein indicator solution. Appearance of pink colour confirms presence of sodium carbonate indicating high pH of the soil. However, exact nature of the soil sodicity can be assessed after depth-wise soil sampling and diagnostic testing in the soil testing laboratory.

5.2.1.4 Infiltration

Water infiltration is restricted as the soil dispersion hardens the soil surface, thus making it difficult for plants to establish and grow. The major implications associated with decreased infiltration due to sodium-induced dispersion include reduced plant available water and increased surface runoff and erosion of top soil.

5.2.1.5 Hydraulic Conductivity

Soil dispersion results not only in restriction of water entering the soil but also affects soil hydraulic conductivity. Hydraulic conductivity implies to the rate of water that flows through the soil. A soil with well-defined structure comprises of a large number of macropores, cracks and fissures which allow relatively rapid flow of water through the soil. In soils where sodium-induced dispersion occurs, it causes loss of soil structure, and the hydraulic conductivity is also reduced. Restricted passage of water through the soil results in swollen upper soil layer and waterlogging. Thus, the anaerobic condition in soils causes reduced or poor plant growth and decreases organic matter decomposition rates. This decrease in organic matter decomposition causes soils to become infertile as in the case of black alkali soils.

5.2.1.6 Surface Crusting

Surface crusting is a common characteristic of sodium-affected soils. The main causes of surface crusting are (1) physical dispersion caused by impact of raindrops or irrigation water and (2) chemical dispersion, which depends on the ratio of salinity and sodicity of the water applied.

Surface soil crusting due to rainfall is greatly enhanced by sodium-induced dispersion of clay. Dispersion of clay particles within soil water causes plugging of macropores in surface soil by two means: firstly, they block avenues for water and roots to move through the soil and secondly, they form cement-like surface layer when the soil dries. The hardened upper layer, or surface crust, restricts water infiltration and plant emergence.

5.2.2 Chemical Indicators

The distinctive characteristic of saline and sodic soils from the agricultural viewpoint is that they contain sufficiently high concentration of neutral soluble salts that adversely affect the growth of many of the crop plants. The chemical indicators of soil salinity include electrical conductivity (EC), total dissolved solids (TDS), exchangeable sodium percentage (ESP), pH and sodium adsorption ratio (SAR). As per the definition, saline soils are those having an electrical conductivity (of the saturation soil extract) of more than 4 dS m^{-1} at 25 °C (Richards 1954). The dominant soluble salts present are the chlorides and sulphates of Na, Ca and Mg, while nitrates may be present in appreciable quantities in some cases. The most dominant ions present in highly saline soils are sodium and chloride, although calcium and magnesium are usually present in ample quantities to meet the nutritional requirements of crop plants. Soluble carbonates are always absent. Several saline soils contain considerable quantities of gypsum ($CaSO_4.2H_2O$) in the soil profile. The pH of the saturated soil paste is always less than 8.2 and more often close to neutrality (Abrol et al. 1980).

The plant growth is affected by the presence of dissolved salt concentration in the soil solution at any particular time. However, it is extremely difficult to measure the soil solution salt concentration at the usual field moisture conditions due to problems in sampling. A simplified procedure consists of mixing the soil sample with sufficient quantities of water to produce a saturated soil paste. The soil solution is then extracted for measuring the electrical conductivity. This measure of the electrical conductivity (EC) in the saturation extract has an advantage as the saturation percentage is directly related to field moisture range. At a considerable textural range, the saturation percentage is approximately four times the soil moisture content held at 15 atmospheres which closely approximates the wilting percentage. The concentration of soluble salts in the saturation extract is about one-half of the concentration in the soil solution at the upper end of the field available moisture and about one-fourth the concentration that the soil solution will have at the dry end of the available moisture range (Richards 1954).

The conductivity of most soil saturation paste extracts is only a fraction of a Siemens per metre (standard unit of conductance), so for convenience, conductivities of soil extracts are expressed in deci Siemens (dS) per metre at 25 °C. The measurement of EC is quick and sufficiently accurate for most purposes. For determination of EC, the solution is placed between two electrodes of constant geometry and constant distance of separation. When an electrical potential is imposed, the amount of current varies directly with the presence of total concentration of dissolved salts. The current is inversely proportional to the resistance offered in soil solution at constant potential and can be measured with a resistance bridge. Both field and laboratory procedures are available for measuring soil salinity or EC (Hardie and Doyle 2012). In the field, soil salinity can be determined by the geospatial measurement (ECa) using different devices. The field measurement of ECa normally requires calibration for the actual salt content by conducting laboratory analyses.

During recent past, several empirical relationships have been developed by researchers for converting one type of analysis to another. The four-electrode technique for measuring bulk soil electrical conductivity has been developed (Rhoades 1976) for use on irrigated soils and on dry land saline seeps in the field. This technique has great potential for measuring soil salinity directly in the field without any soil sampling or subsequent laboratory analysis. This can be used to a great advantage for diagnosing and monitoring changes in salinity due to season or cultural practices including cropping, etc.

Soil category	Guidelines
Saline	In saturated paste extract, the ratio of soluble ions should be $(CO_3 + HCO_3)/(Cl + SO_4) < 1$, $Na/(Cl + SO_4) <1$
Sodic/ alkali	In saturated paste extract, the ratio of soluble ions should be $(CO_3 + HCO_3)/(Cl + SO_4) > 1$, $Na/(Cl + SO_4) >1$

5.2.2.1 Laboratory Investigations for Diagnosis

5.2.2.1.1 Electrical Conductivity

Generally, in soil testing laboratories, soil salinity is assessed by determining either the total soluble salts (TSS) by evaporation of a soil water extract or it can be determined from the electrical conductivity of soil saturation extract (ECe) of either a 1:2 soil to water (w/v) or a saturated paste. Soil extraction with water is a commonly used procedure that simulates field conditions. In the reports, the EC values need to be reported specifying extraction method used and to the nearest 0.01 dS m^{-1}. The soil extraction varies with respect to soil texture and is related to soil-water contents under most of the field conditions, while using a conductivity metre, it should be calibrated with specific calibration solutions (0.1 M KCl having EC value of 12.9 dS m^{-1} at 25 °C). It was indicated by Corwin and Lesch (2013) that although the procedures for measuring soil salinity appear relatively simple, differences in methodology have considerable influence on the measured values and the interpretation of its results. If there is delay in the soil EC measurement after obtaining an extract, add 0.1% sodium hexametaphosphate $[(NaPO_3)_6]$ solution to prevent the precipitation of $CaCO_3$. TDS and EC values are closely correlated in soil solution.

The content of total salt in the soil solution is represented in three ways, i.e. milligrammes per litre (mg L^{-1}), millimole per litre (mmol L^{-1}) or electrolyte conductivity expressed in dS m^{-1}. Although EC has the units of Siemens m^{-1}, it is commonly reported in deci Siemens m^{-1} (dS m^{-1}) which is equivalent to the earlier unit expressed in millimhoscm^{-1} (mmhoscm^{-1}) (1 dS m^{-1} = 1mmhoscm^{-1}). Electrolyte conductivity is one of the simplest representations and easy to measure the flow of current through the soil water. All the three units are related with each other. The relation between mmol L^{-1} and EC is

$$\text{mmol}\ \text{L}^{-1} = 10 \times \text{EC} \qquad (0.1 < \text{EC} < 5.0)$$

The relation between mg L^{-1} and EC is

$$\text{mg}\ \text{L}^{-1} = 0.64 \times \text{EC} \qquad (0.1 < \text{EC} < 5.0)$$

In the equation, the value of the factor increases with increasing EC (greater than 5 dS m^{-1}) and tends to be near unity at very high level of salinity. These relations are only approximate and can be obtained by plotting the values for several common salts present in the soils. The ionic composition in mmol L^{-1} is converted to mg L^{-1} by simply multiplying it with its equivalent weight.

The electrolyte conductivity has the advantage of simplicity in its measurement because it can be readily measured in the field or in the laboratory by using a portable conductivity metre. It is closely related to the sum of cations (or anions) as determined chemically, and it usually correlates directly with the total dissolved solids. It is common to express the conductivity at common moisture and temperature as the electrolyte conductivity depends upon the moisture content and the temperature. The total soluble salt concentration is estimated by determining the EC of the soil saturation extract at 25 °C. Most of the conductivity metres are provided with temperature correction. However, if such correction is not provided, the electrolyte conductivity so determined needs to be corrected for temperature.

5.2.2.1.2 Total Dissolved Solids and Major Ions

The term *total dissolved solids (TDS)* implies to the total amount of soluble salts in a soil-saturated paste extract expressed in parts per million (ppm) or milligram per litre (mg L^{-1}) that contributes to salinity problems. The dissolved salts release cations (positive charge) and anions (negative charge) to the water. The major cations contributing to soil salinity include Ca^{2+}, Mg^{2+}, Na^+ and K^+, and the major anions contributing to soil salinity are SO_4^{2-}, Cl^-, HCO_3^-, CO_3^{2-} and NO_3^-.

In the laboratory, the TDS is determined, and generally it is reported in unit of ppm or mg L^{-1} of salts. For converting the ppm to mmol or meq L^{-1}, the values can be obtained by dividing the values as per the following table for respective ion.

Ion	Molecular weight	Valency	mg L^{-1} (ppm) to mmol L^{-1}	mg L^{-1} (ppm) to meq L^{-1}
Ca^{2+}	40.1	2 (+)	40.1	20.0
Mg^{2+}	24.3	2 (+)	24.3	12.2
Na^+	23.0	1 (+)	23.0	23.0
K^+	39.1	1 (+)	39.1	39.1
SO_4^{2-}	96.1	2 (−)	96.1	48.0
CO_3^{2-}	60.0	2 (−)	60.0	30.0
Cl^-	35.5	1 (−)	35.5	35.5
HCO_3^-	61.0	1 (−)	61.0	61.0
NO_3^-	62.0	1 (−)	62.0	62.0

If the laboratory reports are in ppm (mg L^{-1}), it can be converted from ppm to mmol or meq by dividing the numbers in the above table

The ratio of TDS to EC of various salt solutions ranges from 550 to 700 ppm per dS m^{-1}, depending on the compositions of the solutes in the water. For soil extracts in the EC range from 3 to 30 dS m^{-1}, TDS can be estimated using the formula below.

Simple relationships are used to convert EC to TDS, or vice versa:

$$\mathrm{TDS}\left(\mathrm{mg\,L^{-1}\ or\ ppm}\right) = \mathrm{EC}(\mathrm{dS\,m^{-1}}) \times 640(\mathrm{EC\ \ from\ \ 0.1\ \ to\ \ 5\,dS\,m^{-1}})$$
$$\mathrm{TDS}\left(\mathrm{mg\,L^{-1}\ \ or\ \ ppm}\right) = \mathrm{EC}(\mathrm{dS\,m^{-1}}) \times 800(\mathrm{EC} > 5\,\mathrm{dS\,m^{-1}})$$

The US Salinity Laboratory (Richards, 1954) also used the following empirical relationship between EC and the total soluble salt concentration (TSS, ***mmol L***$^{-1}$).

5.2.2.2 Soil pH Measurement

The measurement of soil pH in the saturation extract is a significant diagnosis of salt-affected soils. Soil pH of saturated soil paste and pH of 1:2 soil-water suspensions are related and presented in Fig. 5.3 (Abrol et al. 1988). It can be observed that pH of 1:2 soil-water suspension (pH_2) is greater than the pH of saturated soil-paste (pHs) by about 1 unit. Therefore, for characterizing sodic or alkali soils, if the pH is measured in 1:2 soil-water suspension, the limiting pH value will be about 9.0 instead of 8.2.

In highly saline soils, the pH of saturated soil paste is around neutral because of the pH of the neutral salts constituting most of the solutes in the soil solution.

With a high soil-water ratio as represented by the saturated paste, the pH varied from 7.1 in the highly saline soil to 8.0 in the nonsaline soil. On diluting the system, soil-water ratio of 1:5 resulted in a pH of 7.8 for highly saline soil and 8.7 for the nonsaline soil. The difference between pH of the saturated paste and 1:2 or 1:5 soil-water suspension was observed to be greater in sodic compared to non-sodic or saline soils. This suggests that a difference of about 1 pH unit between the two readings indicates that the soil contains more than 15% exchangeable sodium. From this it can be inferred that when properly measured, soil pH can be used as a criteria for distinguishing sodic soil from normal or saline soils. However, opinions vary as to the appropriate method of making pH readings, but it is desirable to select a specific method and follow it closely, so that the readings will be consistent to properly diagnose the soil. The method used should be described precisely so as to aid others in the interpretation of results.

5.2.2.3 Exchangeable Sodium Percentage (ESP)

Soil has a definite adsorption capacity for the positively charged salt constituents like calcium, magnesium, potassium, sodium, etc. which is termed as the cation

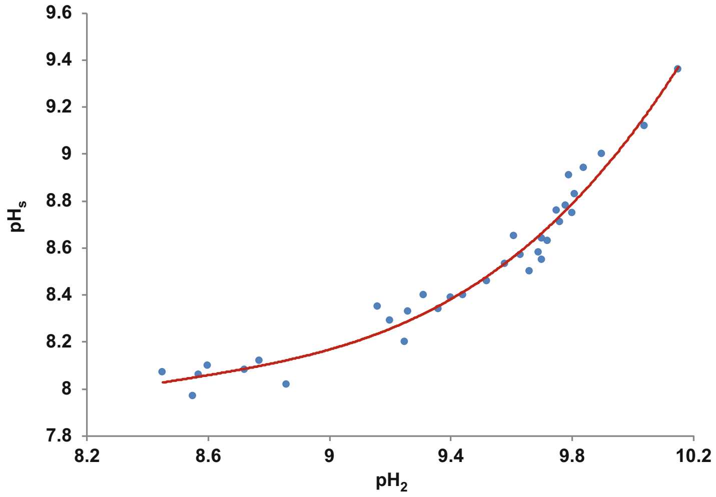


Fig. 5.3 Relationship between soil pH_2 and pHs

exchange capacity of the soil. The different cations adsorbed can be exchanged to the extent of exchange depending upon their relative concentrations in the soil solution, the valency and size of the cation, nature and amounts of other competitive cations there in the soil solution or available on the exchange complex, etc. Exchangeable sodium percentage (ESP) is the amount of adsorbed Na on the soil exchange complex expressed in percent of the total cation exchange capacity of soil in milliequivalents per 100 g of soil. Thus, exchangeable sodium percentage (ESP) is equated as

$$\text{ESP} = \frac{\text{Exchangeable Sodium}(\text{meq}/100\,\text{g soil})}{\text{Cation Exchange Capacity}(\text{meq}/100\,\text{g soil})} \times 100$$

We can find the experimental details for measuring ESP in several publications (Richards 1954; FAO 1970; Hesse 1971). However, measured values of cation exchange capacity and exchangeable cations can vary significantly depending on the method used for determination. The data determined by the same method should only be compared, which means that during survey and monitoring, the same laboratory methodology must be adopted.

5.2.2.3.1 Relationship Between pHs, pH_2 and ESP of the Alluvial Soils

Like EC, pH_2 and pHs are also related, pH_2 being higher than pHs. The difference increases with increase in pHs (Table 5.2, Gupta 1972).

It is apparent that a typical alkali or sodic soils have high pH and high ESP. The pH is more than 9 in all layers, and ESP exceeds 75 at least in surface layers of the soil profile (Gupta and Gupta 2014). Although the electrical conductivity (EC) of the alkali soil is also high at least in top layers, a chemical amendment (preferably gypsum) is required to reclaim this land.

The laboratory estimation of ESP and gypsum requirement of sodic soil is tedious, and most of the soil testing laboratories either do not have facility for ESP or gypsum requirement analysis or lack expertise in estimation, so a model was developed to estimate ESP and gypsum requirements based on soil pH values. The mobile application “GypCal” in English and Hindi was developed (Fig. 5.4) to promote judicious use of chemical amendment gypsum for reclamation of sodic soil using soil pH as input, and this application is made freely available for download through Google Play Store.

Table 5.2 Relationship between pH and ESP of sodic soils

pH_2	pHs	ESP
8.5–9.2	8.0–8.2	<20
9.2–9.4	8.2–8.4	20–35
9.4–9.7	8.4–8.6	35–50
9.7–9.8	8.6–8.8	50–65
9.8–9.9	8.8–9.0	65–75
9.9–10.6	9.0–9.2	85–100

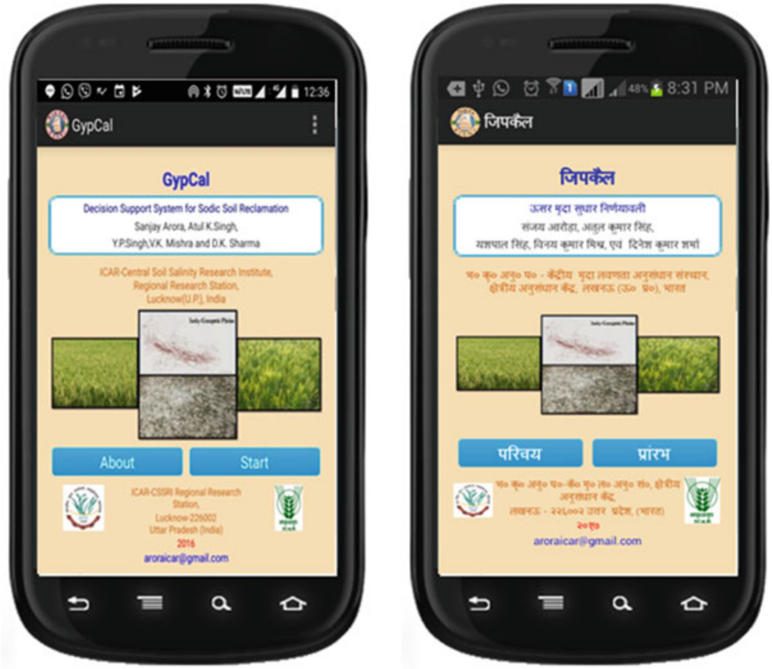


Fig. 5.4 Mobile application "GypCal" (left in English; right in Hindi) for use in estimating gypsum requirement of sodic soils

5.2.2.4 SAR as an Index of Sodicity

Laboratory determination of exchangeable sodium percentage (ESP) is tedious and time-consuming, and there is possibility of errors. During determination, incomplete removal of index salt solution while washing step in CEC determinations, can result in high CEC values with low ESP estimates. Likewise, hydrolysis of exchangeable cations during the removal of the index salt solution, fixing of NH_4 ions from the index or replacement solution by the minerals in soil and the dissolution of $CaCO_3$ or gypsum in the index or replacing solutions can result in low values of CEC, therefore estimating high ESP. Problems of CEC and ESP determinations are also observed in soils of high pH dominant in zeolite minerals. The minerals (e.g. analcime) contain replaceable monovalent cations in their lattice structure which are readily replaced by monovalent cations used as the index or replacement cation from solution, resulting in unusually high ESP values (Gupta et al. 1985). In order to overcome some of these problems in determinations, several workers prefer to obtain an estimate of the ESP from the saturated soil extract. It is proposed that the sodium adsorption ratio (SAR) of the soil solution adequately defines the soil sodicity and is quantitatively related to the ESP of the soils (Richards 1954). Sodium adsorption ratio, SAR, is thus defined by the equation

$$\mathrm{SAR} = \frac{[\mathrm{Na}^{+}]}{\sqrt{\frac{([\mathrm{Ca}^{2+}]+[\mathrm{Mg}^{2+}])}{2}}}$$

where all concentrations are in mmol (+p) per litre.

Although in some studies it has been shown that grouping calcium and magnesium in the above equation is not firmly convincing, there appears not much loss in accuracy when it is done. However, in many laboratories, calcium plus magnesium (Ca + Mg) in the soil extracts is estimated as a single determination – where it is convenient to group these two elements together for the calculation of SAR. The calcium plus magnesium concentration is divided by two as most ion exchange equations express concentrations as mol per litre or mmol per litre rather than mmol (+p) L^{-1}. The prediction of exchangeable sodium status of soils from the SAR of the saturated soil extract is relatively better since the two are related by the expression:

$$\mathrm{ESP} = 100\frac{[\mathrm{Na_{ex}}]}{[\mathrm{Ca_{ex}} + \mathrm{Mg_{ex}}]} = \mathrm{K_G}\frac{\mathrm{Na}^{+}}{\frac{[\mathrm{Ca}^{++}+\mathrm{Mg}^{++}]^{\frac{1}{2}}}{2}} = \mathrm{K_G}\ \ \mathrm{SAR}$$

In these equations, the exchangeable ion concentrations are in cmol (+p) kg^{-1} (the subscript ex indicates exchangeable), and $\mathrm{K_G}$ is the exchange constant called Gapon's constant. There is a linear relationship between SAR of the soil solution and ESR up to an ESP of about 50 so that SAR of the soil solution can be used as a fair measure of the exchangeable sodium status of soils as evident from many reports. For a better estimate of exchangeable sodium, the value of constant $\mathrm{K_G}$ needs to be determined experimentally for each major group of soils. The $\mathrm{K_G}$ value reported by salinity laboratory workers (Bower 1959) for a group of soils from Western United States has been widely used. However, up to SAR of the saturation extract of about 30, the ESP values are roughly similar to SAR, but above this, they diverge and the full expression above must be used.

Under field conditions, plant growth is severely affected due to combination of two or more factors depending on the level of exchangeable sodium, the nature of the crops and the overall management. Table 5.3 gives the approximate extent of hazard in relation to ESP and crops.

5.2.2.5 Electrochemical Stability Index (ESI)

The effect of a sodium salt is two-fold: as an electrolyte the sodium salts (e.g. NaCl, $\mathrm{Na_2SO_4}$ or $\mathrm{NaNO_3}$) coagulate, while as an exchangeable cation, sodium tends to favour dispersion. In sodic soil having high ESP, clay dispersion declines as the salt concentration of the soil solution increases. On the other hand, in sodic soil where the salt concentration is negligible, the soil will disperse easily (UNSW 2007). It can be commonly seen to occur when rainwater falls on the sodic soil. The electrochemical stability index (i.e. ESI) is used to express the relationship between sodicity and salinity.

Table 5.3 Exchangeable sodium percentage (ESP) and sodicity hazard

Approx. ESP	Sodicity hazard	Remarks
<15	None to slight	Adverse effect of ESP on crop growth and yield in various classes occurs according to the relative tolerance of crops to excess sodicity, whereas only sensitive crops are affected at ESP levels below 15 and only extremely tolerant native grasses can grow at ESP above 70 to 80
15–30	Light to moderate	
30–50	Moderate to high	
50–70	High to very high	
>70	Extremely high	

The ESI is estimated by the ratio of the electrical conductivity and the exchangeable sodium percentage (ESP) of the soil. A tentative critical ESI value for Australian cotton soil is 0.05. An economically viable response to gypsum and/or lime can be expected where ESI values are at or below the level of 0.05. While managing soil structural decline due to presence of excess sodium on the exchange complex, gypsum ($CaSO_4.2H_2O$) can be applied. The effect of the addition of gypsum in this way is two-fold. In the first instance, as the solubility of gypsum is less, the soil solution salinity increases. The effect is short-lived as the gypsum is ultimately leached, but this temporary increase in soil solution salinity mitigates the impact of the high soil ESP. In the long term, the excess calcium entering the soil solution exchanges with the sodium and magnesium on the clay surface. During subsequent irrigation or rainfall, both of these may be leached out. This results in removal of sodium and magnesium, and the calcium is left behind to initiate the process of aggregation.

5.2.2.6 Relationship Between Salinity and Sodicity (EC vs SAR) and Soil Physical Properties

The relationships between soil salinity and its flocculating effects and sodicity and its dispersive effects influence whether or not soil will stay aggregated or become dispersed under various salinity and sodicity combinations. On irrigation with low salinity water, this water flows into the spaces between clay particles (micropores), and if salinity of the irrigation water is low relative to soil salinity, swelling and dispersion of clay particles may result. However, irrigation water with higher salinity than the soil tends to bind particles maintaining soil structure.

Researches since many decades have been conducted to determine the relationship between salinity (EC) and sodicity (SAR) of irrigation water and its effects on soil physical properties. It has now been understood well enough the relation in order to make accurate predictions of how specific soils will behave when irrigated water contains different levels of salts and sodium. The key concerns in the relationship between salinity and sodicity of irrigation water are the effects on infiltration rates and hydraulic conductivities of soil.

5.2.2.7 The Swelling Factor

Salinity promotes soil flocculation and sodicity promotes soil dispersion. The combination of salinity and sodicity of soils is measured by the swelling factor, which is the amount a soil is likely to swell with different combinations of salinity and sodicity. Basically, the swelling factor predicts whether sodium-induced dispersion or salinity-induced flocculation will more greatly affect soil physical properties. Researchers have been able to get a good idea of the swelling factor by using Fig. 5.5 where it is possible to draw a line from the sodium content (adjusted ESP) in the left column to the appropriate salt concentration in the right column. The line intersects the middle column, the swelling factor, indicating how much the soil will swell. For

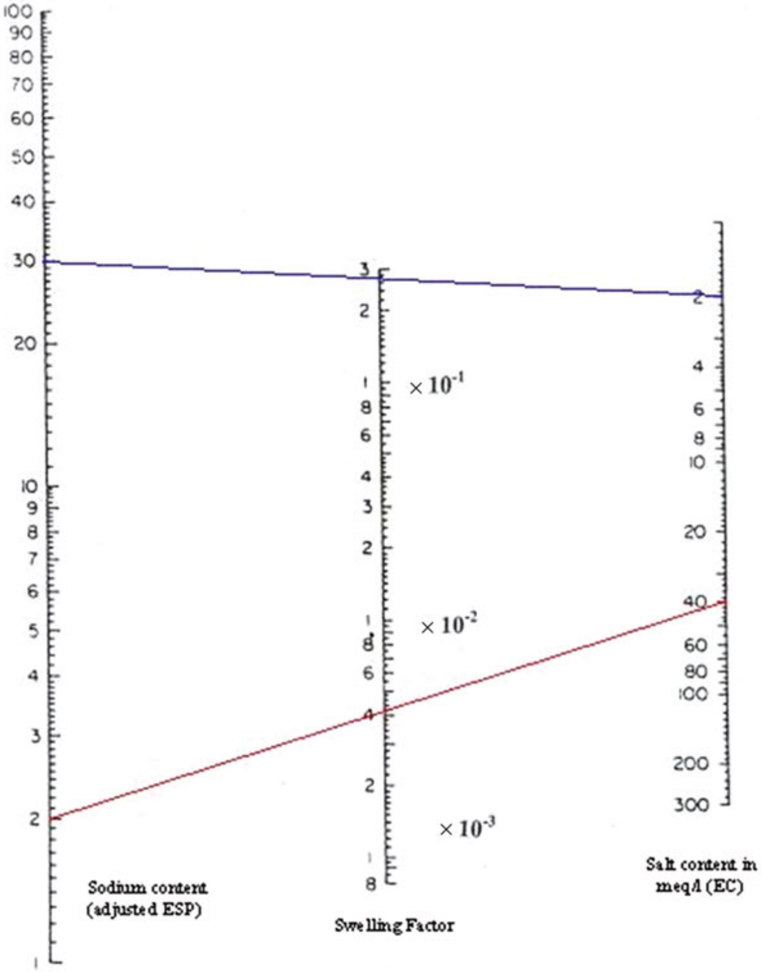


Fig. 5.5 Swelling factor as a function of Na content (adjusted ESP) of soil and concentration of salt in soil water. (After McNeal 1968)

example, drawing a line between adjusted ESP of 2 and an EC of 40 meq L^{-1} yields a swelling factor of 0.0041 which indicates that dispersion is not a problem in this case. However, a combination of adjusted ESP of 30 and EC of 2 will yield a swelling factor of 0.28 which indicates the likely dispersion. This helps to show how the dispersive effects of soils with high ESP can be lessened with the flocculating effects of irrigation water with high EC (salinity).

5.2.2.8 Infiltration Rates

Another approach to judge the effects of salinity (EC) and sodicity (SAR) on soil physical properties is to assess potential impacts of various irrigation water qualities on soil infiltration rates. The relationship between salinity and sodicity and infiltration rates is presented in Fig. 5.6. For example, severe problems are likely if the irrigation water has low salinity and high sodicity. At SAR of 15, a severe reduction in infiltration will occur at an EC of 1 dS m^{-1}. The EC of 2.5 or less results in a slight to moderate reduction in soil infiltration, while with an EC greater than 2.5, there will likely not be a reduction in infiltration. Similarly, Table 5.4 numerically defines the relationship between EC, SAR and infiltration rates.

There are certain factors such as climate, soil type, crop and plant species and management practices that also need to be accounted for when determining acceptable levels of salinity and sodicity of irrigation water. Rainfall also plays an important role in the relationship between salinity and sodicity and soil physical properties. Heavy rainfall can flush salts beneath the root zone, but often cannot significantly reduce amounts of sodium bound to the soil. Therefore, rainfall can reduce the potential for soil aggregation from salts and increase the likelihood that

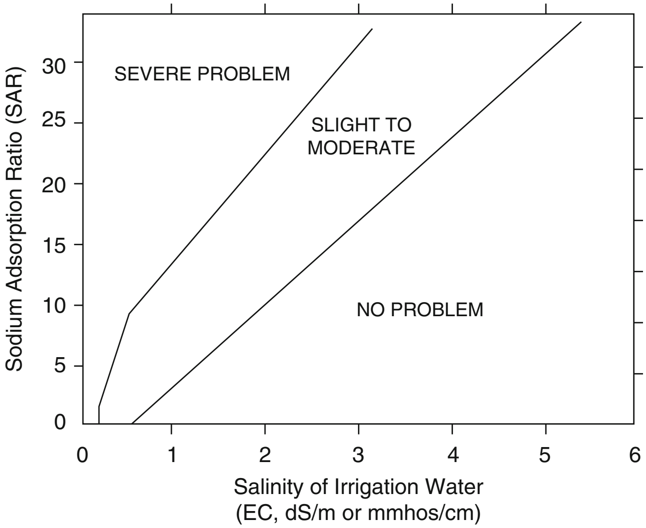


Fig. 5.6 Potential for reduction in infiltration rates resultant of various combinations of EC and SAR of applied water. (After Hanson et al. 1999)

Table 5.4 Relationship between EC, SAR and infiltration rates

	EC (dS m^{-1})		
SAR	No problem	Slight to moderate problem	Severe problem
0–3	>0.9	0.9–0.2	<0.2
3–6	>1.3	1.3–0.25	<0.25
6–12	>2.0	2.0–0.35	<0.35
12–20	>3.1	3.1–0.9	<0.9
20+	>5.6	5.6–1.8	<1.8

sodium-induced dispersion may occur. On the basis of physical and chemical indicators, the distinguishing features are summarized to identify the characteristic of saline and sodic soil (Table 5.5; Abrol et al. 1988).

5.3 Bioindicators

Saline soils can be recognized by the patchy growth of crops in the field and often by the presence of white salt crusts on the soil surface. In mild problem due to salt, blue-green tinge is often observed on growing plants. Stunted plant growth and barren spots may appear in cereal or forage crops growing on saline soils. The extent and frequency of barren spots is generally an indication of the salt concentration in the soil. The crop appearance may be irregular in vegetative vigour, where the salinity level is not sufficiently high to cause barren spots.

In a uniform field having moderate salinity, it can often go undetected because it causes no apparent injuries other than restricted plant growth. The plant leaves in salt-infested areas may be smaller and darker blue-green in colour compared to the normal leaves. There is increased succulence often due to salinity, particularly if there is high concentration of chloride ions in the soil solution. In salt-affected soils, plants often have the same appearance as the plants growing under drought stress conditions although the plant wilting is much less prevalent due the osmotic potential of the soil solution that usually changes gradually and plants adjust their internal salt content to maintain turgor and thus avoid wilting.

Due to specific element toxicities, symptoms such as marginal or tip burn of leaves occur only in woody plants. Chloride and sodium ions and boron are the elements most usually associated with toxic symptoms. However, non-woody plant species may generally accumulate as much or more of these elements in their leaves without showing apparent symptom as in the woody species.

5.3.1 Effect of Soil Salinity and Ion Toxicity on Crop Growth and Yield

Saline water can also affect plant growth and yield by osmotic potential and toxic effect of specific ions such as B, Na^+ and Cl^-, in addition to the indirect effects of salinity, sodicity and pH on soil fertility. Salinity reduces water uptake by plants, and

Table 5.5 Distinguishing features of saline and sodic soils

Characteristics	Saline soils	Sodic soils
1. Chemical	(a) Saline soils are dominated by neutral soluble salts such as chlorides and sulphates of sodium, calcium and magnesium	(a) Substantial quantities of neutral soluble salts are generally absent. Presence of measurable to appreciable quantities of salts capable of alkaline hydrolysis, e.g. Na_2CO_3
	(b) Soil saturation paste pH is less than 8.2	(b) Soil saturation paste pH is more than 8.2
	(c) The saline soils have electrical conductivity of the saturated soil extract of more than 4 dS m^{-1} at 25 °C	(c) The electrical conductivity of the saturated soil extract is generally <4 dS m^{-1} at 25 °C but may be more if appreciable quantities of Na_2CO_3, etc. are present. In sodic soils, the exchangeable sodium percentage (ESP) of 15 or more is the generally found
	(d) There is generally no well-defined relationship between saturated soil paste pH and exchangeable sodium percentage (ESP) of the soil or the sodium adsorption ratio (SAR) of the saturation extract	(d) The relationship between pH of the saturated soil paste and the exchangeable sodium percentage (ESP) of the soil or the SAR of the saturation extract is well defined. Thus, the pH can serve as an approximate index of soil sodicity (alkali) status
	(e) Although sodium is generally dominant, the soil solution also contains appreciable quantities of divalent soluble cations like Ca and Mg	(e) Sodium is the dominant soluble cation, and the high pH of the soils results in precipitation of soluble Ca and Mg resulting in their reduced concentration in the soil solution
	(f) Soils may contain significant quantities of sparingly soluble calcium compounds, e.g. gypsum	(f) Gypsum is nearly always absent in such soils
2. Physical	(a) Due to the presence of excess neutral soluble salts, the clay fraction is flocculated, and the soils have a stable structure	(a) Due to excessive exchangeable sodium and high soil pH, dispersion of clay and the soils have an unstable structure
	(b) Soil permeability to water and air and other physical characteristics are generally good as in normal soils	(b) Permeability of soils to air and water is generally restricted, and the physical properties of these soils become worse with increasing levels of exchangeable sodium associated with high pH
3. Effect on plant growth	In saline soils plant growth is adversely affected mainly because of:	In sodic soils plant growth is adversely affected due to:
	(a) The effect of excess salts on the osmotic pressure of soil solution resulting in reduced availability of water	(a) The dispersive effect of excess exchangeable sodium resulting in poor physical properties

(continued)

Table 5.5 (continued)

Characteristics	Saline soils	Sodic soils
	(b) Toxicity of specific ions, e.g. Na, Cl, B, etc.	(b) The effect of high soil pH on nutritional imbalances including a deficiency of calcium
		(c) Toxicity of specific ions, e.g. Na, CO_3, Mo, etc.
4. Geographic distribution	These saline soils dominate in arid and semiarid regions	The sodic soils are generally dominated in semiarid and subhumid regions
5. Groundwater quality	Groundwater in saline soil areas has generally high electrolyte concentration and a potential salinity hazard	Groundwater in sodic areas has generally low to medium electrolyte concentration, and some of it may have residual sodicity causing a potential sodicity hazard
6. Soil amelioration	Amelioration of saline soils essentially requires removal of soluble salts beyond the root zone through leaching and drainage. Generally no need of application of amendments	Sodic soils essentially require the replacement of sodium in the soil exchange complex by calcium through use of soil amendments along with leaching and drainage of salts resulting from reaction of amendments with exchangeable sodium

Source: Adapted from Abrol et al. (1988)

high levels of salt hinder water absorption, inducing ***physiological drought*** in the plant. Although the soil may contain adequate amount of water, plant roots are unable to absorb it because of unfavourable osmotic pressure. This is referred to as the osmotic or water-deficit effect of salinity (***Osmotic potential*** $= -$ ***EC*** $\times$ *0.4*). Generally plants are most sensitive to salinity during seed germination and early growth.

The relative yield (RY) of a crop is related to salinity (EC) of soil-saturated extract, i.e. EC_e, by:

$$\mathrm{RY}(\%) = 100 - \mathrm{Slope} \times [\mathrm{EC_e} - \mathrm{EC_e}(\mathrm{Threshold\ \ value})]$$

Threshold is the value of EC of saturated extract (ECe) when yield starts decreasing.

Slope: % of yield decrease when ECe increased by 1 dS m^{-1}.

5.3.2 Distinct Changes in Vegetation

The distinctive changes in the vegetation may be caused by numerous factors, including changes in the concentration of salt and/or water in the soil.

For instance, a stand of swamp oak (*Casuarina glauca*) appearing on a high slope could suggest the occurrence of groundwater springs as this plant species generally prefers wet, swampy and saline areas. The groundwater springs and perched water tables are very common in urban and peri-urban environments due to changes in the volume and flow paths of water in the landscape.

Yellowing or stunted growth of plant may indicate that plant species cannot cope with the level of water and/or salt in the soil. Under severe cases complete wilting or dead vegetation is observed.

5.3.3 Salinity Indicator Plant Species

Salinity indicator plant species are those species that are commonly observed in salt-affected and/or waterlogged areas. Some of these species are exclusively found in sodic or saline or waterlogged conditions and not elsewhere, while many are found both in saline and normal conditions.

5.3.4 Indicators of Inland Saline Soils

All true halophytes (described later) such as species of *Suaeda*, *Atriplex*, *Salicornia*, *Salvadora*, *Tamarix* and *Haloxylon* along *with Aeluropus lagopoides*, *Heliotropium curassavicum*, *Cressa cretica*, *Sporobolus marginatus*, *S. diander*, *S. tremulus*, *Fagonia cretica*, *Portulaca oleracea* and *Zygophyllum simplex* are the indicators of salinity. *Cressa cretica* and *Salvadora* are dominant species in saline agricultural lands of Indian west coast (Arora et al. 2014a; Rao et al. 2017).

Among other salt-tolerant species, though cannot be claimed as indicators, include species of *Acacia*, *Prosopis*, *Capparis*, *Ziziphus* and *Cordia*. *Balanites roxburghii*, *Calotropis procera*, *Holoptelea integrifolia*, *Leptadenia pyrotechnica*, *Lycium barbarum*, *Maytenus emerginata*, *Mimosa hamata*, etc. among woody species and *Eleusine compressa*, *Sphaeranthus indicus*, *Solanum xanthocarpum*, *Citrullus colocynthis*, *Peganum harmala*, *Schoenfeld gracilis*, *Dactyloctenium sindicum*, *D. aegyptium*, *Dichanthium annulatum*, *Panicum spp., Cynodon dactylon*, etc. among herbaceous species are frequently found distributed in saline communities. Dagar (2003) and Dagar and Singh (2007) listed 1140 salt-tolerant species (including coastal areas) distributed under 541 genera and 131 families. For the list of these species, please see these publications.

5.3.5 Indicators of Sodicity

The sodic/alkali soils support very restricted natural flora, comprising only a few salt-tolerant species. Tree species such as *Capparis decidua*, *C. sepiaria*, *C. zeylanica*, *Salvadora oleoides*, *Clerodendrum phlomidis*, *Acacia nilotica* and

Ziziphus nummularia are among the prominent woody species. *Prosopis juliflora* (an introduced species) has established itself widely forming gregarious patches, but it is also found on all degraded lands. At slightly low pH (up to 9), *Acacia leucophloea*, *A. eburnea*, *Mimosa hamata*, *Prosopis cineraria*, *Butea monosperma*, *Diospyros tomentosa*, *Balanites roxburghii*, *Lycium barbarum*, *L. europaeum*, *Maytenus emerginata* and *M. royleanus* are frequent, but most of these are also found on other degraded lands in dry ecologies and hence cannot be adjudged as indicator species. Among bushes of *Capparis* and *Salvadora*, climbers such as *Asparagus racemosus*, *Cocculus pendulus*, *C. hirsutus*, *Cayratia trifolia*, *Momordica dioica*, *Mukia maderaspatana* and *Ichnocarpus frutescens* are quite frequent. *Adhatoda zeylanica*, *Calotropis procera* and *Achyranthes aspera* are found in bushes as well as isolated associations. Among herbaceous species *Leptochloa fusca* is a known grass for its sodicity tolerance particularly during rainy season and along with *Desmostachya bipinnata*, *Sporobolus marginatus*, *S. diander*, *Chloris barbata*, *C. virgata*, *Melanocenchris jacquemontii*, *Trianthema triquetra*, *Kochia indica* and *Croton bonplandianum* are indicators of high pH soils. *Suaeda maritima* and *S. fruticosa* are also found, but these along with many other species are indicators of salinity. When protected from grazing, many more species do appear in these soils which include *Cassia occidentalis*, *C. tora*, *Abutilon indicum*, *Dactyloctenium aegyptium*, *Dichanthium annulatum*, *Echinochloa colona*, *Cynodon dactylon*, *Cenchrus setigerus*, *C. ciliaris*, *Cyperus* spp., *Setaria anceps*, *Trianthema portulacastrum*, *Cassia tora*, *C. occidentalis*, *Abutilon indicum*, *Eclipta prostrata*, *Chenopodium album*, *C. murale*, *C. ambrosioides*, *Portulaca quadrifida*, *Euphorbia thymifolia*, *Phyllanthus fraternus*, *Amaranthus viridis*, *A. spinose*, *Melilotus alba*, *M. indica*, *Indigofera* spp., *Corchorus* spp., etc. but cannot be called as indicator species.

5.3.6 Indicators of Reed Swamps and Waterlogging

Some species such as sea barley grass (*Hordeum marinum*) and spiny rush (*Juncus acutus*), *Typha australis*, *T. elephantina*, *Phragmites australis*, *Eichhornia crassipes*, *Ipomoea carnea*, *Fimbristylis ferruginea*, *F. littoralis*, *Scirpus littoralis* and many species of *Paspalum* do not appear anywhere else except waterlogged stagnant shallow waters. These form the reed swamps. Besides these, many species of *Juncus*, *Cyperus*, *Fimbristylis*, *Scirpus*, *Echinochloa*, *Paspalum*, *Panicum* and *Leptochloa fusca*, *Vetiveria zizanioides*, *Saccharum spontaneum*, *Sacciolepis interrupta* and *Urochondra setulosa* are frequent in swampy areas, while *Nelumbo nucifera*, species of *Nelumbo* and *Nymphoides* and free-floating *Azolla*, *Eichhornia crassipes*, *Lemna*, *Spirodela* and many green and blue-green algal colonies are common associates of the reed swamps.

5.3.7 Indicators of Coastal Salinity

The mangrove vegetation (mangal formation) occurs in tidal zone where soil is flooded with seawater either permanently or at high tide. There seem to be five vital requirements for extensive mangal development, which include tropical temperatures of more than 20 °C during winter months and the seasonal temperature range not exceeding 5 °C, fine-grained alluvium or alluvial soil, protected seashores, saltwater (mixing frequently with freshwater through creeks and rivers) and large tidal range. Many authors differentiate between the typical or true mangroves on one hand and the accompanying flora on the other (called associate mangroves). Decidedly, true mangroves do not occur elsewhere and are the indicators of tidal zone salinity, while many others though also found associated with mangroves are also found in non-tidal saline areas. Undisputedly the typical mangrove genera are *Bruguera*, *Ceriops*, *Kandelia* and *Rhizophora* (family Rhizophoraceae); *Avicennia* (Avicenniaceae); *Sonneratia* (Sonneratiaceae); *Aegiceras* (Myrsinaceae); *Heritiera* (Sterculiaceae); *Dolichandrone* and *Xylocarpus* (Meliaceae); *Laguncularia*, *Conocarpus* and *Lumnitzera* (Combretaceae); *Nypa* (Arecaceae); and *Scyphiphora* (Rubiaceae). Besides these *Aegialitis rotundifolia* (Plumbaginaceae); *Acanthus ebracteatus*, *A. ilicifolius* and *A. volubilis* (Acanthaceae); and *Excoecaria agallocha* (Euphorbiaceae) are other species of mangroves. At present, the updated lists of true mangrove species of world consist of 82 species (including 11 natural hybrids) of 30 genera from 17 families worldwide. (For detailed list see Raghavan et al. in this volume.)

The important associate mangrove species, which are more frequently found in mangrove stands than elsewhere, include *Aglaia cucullata*, *Arthrocnemum indicum*, *Atriplex stocksii*, *Barringtonia asiatica*, *B. racemosa*, *Brownlowia tersa*, *Caesalpinia crista*, *C. nuga*, *Calophyllum inophyllum*, *Cerbera manghas*, *Clerodendrum inerme*, *Dalbergia spinosa*, *Dendrophthoe falcata*, *Derris heterophylla*, *D. scandens*, *D. sinuata*, *D. trifoliata*, *Dolichandrone spathacea*, *Guettarda speciose*, *Hernandia peltata*, *Hibiscus tiliaceus*, *H. tortussus*, *Intsia bijuga*, *Licuala spinosa*, *Manilkara littoralis*, *Merope angulata*, *Ochrosia oppositifolia*, *Pandanus fascicularis*, *P. foetidus*, *P. furcatus*, *P. tectorius*, *Pongamia pinnata*, *Premna corymbosa*, *Salvadora persica* (on west coast only), *Scaevola taccada*, *Terminalia catappa*, *Thespesia populnea*, *Tournefortia ovata* and *Vitex negundo*. Some species are distributed in restricted habitats. For example, *Arthrocnemum indicum* and *Salvadora persica* are found along Gujarat coast in pure patches, while *Cycas rumphii*, a gymnosperm, is common along Nicobar coast and *Licuala spinosa* is a common palm in Andaman. Climbers such as *Finlaysonia obovata*, *Flagellaria indica*, *Mucuna gigantea*, *Salacia chinensis*, *Sarcolobus globosus*, *Stictocardia tiliifolia*, *Stenochlaena palustris*, *Tournefortia ovata* and *Tylophora tenuis* are quite frequent. *Dischidia nummularia* and *Hoya parasitica* are found hanging on branches very frequently. *Viscum monoicum* and *V. orientale* are common parasite. *Cassytha filiformis*, *Ipomoea pes-caprae*, *I. tuba*, *Sesuvium portulacastrum* and *Spinifex littoreus* are common trailers on sandy beaches. These are mixed up with herbaceous species such as *Aeluropus lagopoides*, *Fimbristylis*

Table 5.6 Marine microbes in different mangrove regions of India (Kathiresan 2009)

No.	Microbe group	East coast	A&N Islands	West coast
1.	Microalgae	199	41	152
2.	Bacteria	58	13	10
3.	Fungi	57	59	80
4.	Actinomycetes	23	5	11
Total		337	118	253

ferruginea, *Halophila beccari*, *Heliotropium curassavicum*, *Launaea sarmentosa*, *Myriostachya wightiana*, *Porteresia (Oryza) coarctata* (dominant grass in Sunderbans), *Salicornia brachiata*, *Scirpus littoralis* (common sedge in stagnant water), *Suaeda fruticosa*, *S. maritima*, *S. monoica*, *S. nudiflora*, *Thuarea involuta*, *Urochondra setulosa* (common grass along Gujarat coast), *Wedelia biflora* and *Zoysia matrella.* For more details of species of both true mangroves and associate mangroves, see Ragavan et al. (Chapter 8 in this publication).

5.3.8 Marine Salt-tolerant Microbes

Mangrove provides a unique ecological environment for salt-tolerant microbial communities such as microalgae, fungi, actinomycetes, bacteria as well as viruses. The microbes fill a number of niches and are primary for the functioning of the mangrove habitats. The mangrove ecosystem is detritus-based that depends on the microbes that are involved in decomposition of the organic matter, making the protein-rich food for fish, recycling of the nutrients and supporting the coastal food web. In order to adapt to diverse physical and chemical conditions of mangroves, the microbes produce novel chemical compounds of unique biological properties. However, the bioprospecting potential of the mangrove-derived microbes is yet to be properly understood for their potential applications as food, fuel, fertilizers and valuable chemicals for pharmaceutical and industrial utility. Kathiresan (2009) has listed 337, 253 and 118 marine microbes from east coast, west coast and Andaman and Nicobar (A&N) Islands, respectively (Table 5.6). (For more details, please see Chapter 7 of Kathiresan in this publication.)

5.4 The Impacts of Salinity on Plants

Salinity may have effects on plants through waterlogging creating anaerobic condition or through osmatic effects or toxic effects due to excessive absorption.

Waterlogging The excess of water in the plant root zone limits availability of oxygen and thus can cause anaerobic conditions. The anaerobic condition inhibits symbiotic microorganism activity as well as prevents normal plant functions. It also causes symptoms such as stunting, foliage discolouration, defoliation, wilting and death in some cases unless the plant gets adapted to these conditions. These symptoms are very analogous to those caused by excess salt.

Osmotic Effects Small quantities of salts are required by plants to carry out the complex metabolic processes involved in photosynthesis and respiration processes. Salts also play a role in water movement between the soil and root. The excessive concentration of salts around plant roots will reduce its ability to take up water. Even in presence of plenty of water in the soil, accumulated salts decrease the osmotic potential or free energy of water. This causes the pressure difference between the water held in the root and the soil to diminish, reducing the movement of water from soil into the root leading to dehydration and wilting of plant leaves and stems. Plant metabolic processes including photosynthesis get limited due to lack of water.

Toxic Effects To compensate for water loss during transpiration, plants need to absorb water, and in saline conditions, small amounts of salt will also enter the plants along with water so the salt concentration inside plants, over time, may cumulatively become toxic.

All plant species vary in their tolerance to salts as some species will be affected by low concentrations, while others can tolerate high salt concentrations. Minor changes in the salt concentration along this sensitivity gradient may have a similar impact on sudden large changes in salt concentration if a critical threshold of salt is reached. Toxicity of specific ions will affect plants in different ways. Internal structural components may be affected, or plant processes may be inhibited. For example, excessive bicarbonate ions can cause stunted plant roots, and a range of salts will cause yellowing of the leaf tips.

5.5 Characteristics of Salt-tolerant (Halophytic) Plants

Halophytes are naturally “salt-loving” plants that grow optimally in an environment with high salinity. Relatively few plant species are halophytes, but all the mangroves and many of their associates are true halophytes among coastal plants, and the members of Chenopodiaceae family among inland species are dominant (Flowers and Colmer 2008). Among others, the most common halophytic plant species include salt marsh cordgrass (*Spartina alterniflora*, *S. gracilis*), salt grass (*Distichlis spicata*), saltbush (*Atriplex lentiformis*) and pickleweed (*Salicornia bigelovii*) (Lin et al. 2002; Bañuelos and Lin 2007). *S. bigelovii* can be cultivated using original seawater for irrigation (Ayars et al. 1993; Ayala and O’Leary 1995). Halophytes may be classified into the following three categories:

1. *True (obligate) halophytes*: These are the plants mainly attaining optimal growth on the saline soil (above 0.5% NaCl level), for example, *Suaeda fruticosa*, *Cressa cretica*, *Aeluropus lagopoides*, *Salsola baryosma*, *Haloxylon recurvum* and *Zygophyllum simplex*.

2. *Facultative halophytes*: These plants obtain optimal growth on saline soil (at 0.5% NaCl concentration) like true halophytes and can also grow on nonsaline soil, e.g. *Trianthema triquetra*, *Tamarix dioica*, *Launaea nudicaulis*, *Eragrostis ciliaris*, *E. pilosa*, *Salvadora persica*, *Pulicaria wightiana* and many others.
3. *Glycophytes or transitional halophytes*: These types of plants grow only at the transition of saline and nonsaline areas and achieve optimal growth at nonsaline niches of the salt basin, e.g. *Sporobolus marginatus*, *S. helvolus*, *Haloxylon salicornicum* and *Dactyloctenium sindicum.* A specific adaptation of halophytes allows them to cope with salt, including the following:
   - *Succulence*

     Succulent plants are those having fleshy leaves that contain a high proportion of water. This water dilutes salt, thus keeping salt levels low within the plant. *Arthrocnemum indicum*, species of *Suaeda*, *Trianthema triquetra*, *Westringia fruticosa*, *Carpobrotus glaucescens*, *Sesuvium portulacastrum*, etc. are the examples.
   - *Short-life cycle*

     Many ephemeral plants such as *Cardamine hirsuta* germinate, flower, produce seeds and complete life cycle in a short period. Many desert ephemerals such as *Arabidopsis thaliana* produce during brief favourable period and avoid drought condition for their survival. These plants have adapted to complete one life cycle before the salt level in the soil becomes toxic and kills them.
   - *Root filtering*

     Salt is prevented from entering the roots of plants that have a greater osmotic pull or ability, such as mangroves and some grasses, to take up water from saline soils.
   - *Salt glands or pumps*

     Salt glands direct the salts to intercellular spaces or pump the salt to organs that excrete salt through specialized cells at the leaf surface. Some saltbushes like *Atriplex* spp. have special type of glands that concentrate salt and pump it to expandable bladders attached to their leaves by thin stalks. These glands burst when full to release out the salt.

5.6 Adaptations Among Plants Against High Salinity

Halophytes are adapted to survive in the range of saline environments. Some of these plant species grow in high-moisture saline areas such as mangrove swamps, others exist in fluctuating moisture conditions in tidal zones, and some others may live in inland saline areas in arid and semiarid climates. In any case, the halophytes must adjust their tissue water potentials to a level that is lower than that of the soil water potential in the habitat where they are growing. The key mechanism used by these plants to obtain sufficient water for growth and development is osmotic adjustment. There are many kinds of adaptations which help these plants to survive and sustain growth in stress conditions. These may include the morphological and anatomical adjustments; seed structure, dormancy and germination alterations; and ecophysiological and biochemical adaptations at various growth stages. Some of the mechanisms used by halophytes to counter the potential toxic effect of high ionic concentrations involve exclusion of salts by the roots, dilution of the ions through succulence, synthesis of organic osmotic compounds that can reduce the need for salt ions and compartmentalization of the excess salt ions into tissues, organs or the vacuoles of cells (Weber 1995). Halophytes need to obtain sufficient ions to maintain growth while avoiding a water deficit or excessive ions. The net result is that the halophytes grow successfully in saline environments where glycophytes cannot grow. Some of the mechanisms to which halophytes adopt have been dealt herewith in brief.

5.6.1 Morphological and Anatomical Adaptations

Under the physical or physiological stress, the leaves of halophytes play an important role and develop certain xeromorphic characteristics like succulence, reduction in surface area, thick cuticle or a cover of waxy layers on epidermis, hairs on stem and leaves, sunken stomata and salt glands. There is an abrupt reduction in the surface area of leaves of some species (e.g. *Salsola baryosma*, *Trianthema triquetra*, *Suaeda fruticosa*, *Tamarix* spp.) during extreme salt stress. The leaves and stems of some species like *Cressa cretica*, *Chloris virgata*, *Sporobolus marginatus*, *S. helvolus* and *Aeluropus lagopoides* remain covered with hairs (trichomes) giving the plant a greyish appearance. Though their effectiveness in reducing the loss of water may be limited, they are able to protect the leaf surface against dust. *Suaeda fruticosa*, *Salsola baryosma*, *Haloxylon recurvum*, *H. salicornicum*, *Cressa cretica*, *Sporobolus marginatus*, *Chloris virgata* and *Aeluropus lagopoides* are characterized by the thick cuticle and a waxy layer. *Calotropis procera* along with wax on leaf and stem surface also develops milky latex. *Capparis decidua* sheds the leaves completely and the function is replaced by the green stem.

Some extreme halophytes lack the ability to excrete salt, and they are highly succulent and thwart the rising of salt concentration by a permanent increase of their water content. They become more and more succulent during their development. *Haloxylon recurvum*, *H. salicornicum*, *Portulaca oleracea*, *Suaeda fruticosa*, *S. nudiflora*, *Salsola baryosma*, *Sesuvium portulacastrum*, *Trianthema triquetra* and *Zygophyllum simplex* are the typical halophytes of Indian saline marshes leading to shrinking in leaves, elongation of cells, higher elasticity of cell walls and smaller relative surface areas, decreasing in extensive growth and having high water content per unit of surface area. Leaves of some succulent halophytes like *Suaeda fruticosa*, *Salsola baryosma* and *Trianthema triquetra* have reduced surface area, when they are exposed to a high salt content in the soil.

Some plants are cumulative halophytes which lack any regulatory mechanism. The salt concentrations therefore rise during the growing season, and when a certain level is reached, the plants die. *Fagonia cretica*, *Vernonia cinerea*, *Eclipta prostrata* and some species of *Cyperus* and *Scirpus* are such examples.

The anatomical features of mangrove leaves do not possess any features that are exclusively associated with them, but these do possess xeromorphic features such as thick and waxy cuticle, sunken or chambered stomata, water storage tissue, palisade-like mesophyll and vascular bundles terminating in tracheid and mucus cells. These features may serve as a protection against water loss because of the difficulty of water absorption from highly saline water, or their presence may be associated with any excess salt present in the cell sap; however, increased succulence may be associated with increased salinity; and the thick cuticle, the sunken or chambered stomata and the mesophyll are related to water conservation.

Water storage tissue is a characteristic feature of nearly all mangrove leaves which may be exclusively hypodermal (e.g. species of *Rhizophora*, *Bruguiera*, *Ceriops*, *Avicennia*), derived from hypodermis plus subsequently modified assimilatory tissue (e.g. species of *Xylocarpus*, *Aegiceras*, *Kandelia*), exclusively deep seated (e.g. *Lumnitzera*, *Sonneratia*) or without any specific water storage tissue (e. g. *Derris*). Mucus cells, which can be regarded as isolated water storage cells or as waste product storage cells, have been recorded from leaves of genera like *Rhizophora*, *Xylocarpus*, *Bruguiera*, *Kandelia*, *Sonneratia*, *Acanthus*, *Scyphiphora*, *Excoecaria* and *Aegiceras*. In many genera isolated sclereids or patches of sclereids are found in the palisade zone or the mesophyll.

Oxalate crystal cells are found in the leaves of plant of Rhizophoraceae family. Removal of water from the leaves and possibly also of salt takes place by means of special hairs, stomata, epidermal cells, epithematic hydathodes and possibly also lenticel hydathodes (Chapman 1976). The lenticels are also present on roots and stems of mangroves. Salt glands, which will also excrete water, were found on the surface of leaves of *Avicennia*, *Lumnitzera*, *Acanthus*, *Aegialitis* and *Aegiceras* (Dagar et al. 1991).

Liphschitz and Waisel (1982) and Breckle (1995) listed active secreting salt glands in species of *Acanthus*, *Avicennia*, *Aegiceras*, *Aegialitis*, *Armeria*, *Aeluropus*, *Andropogon*, *Bruguiera*, *Brachiaria*, *Bouteloua*, *Buchloe*, *Convolvulus*, *Ceriops*, *Chloris*, *Coelocaryon*, *Cynodon*, *Crypsis*, *Cenchrus*, *Chrysopogon*, *Coix*, *Distichlis*, *Dactyloctenium*, *Dinebra*, *Dichanthium*, *Digitaria*, *Echinochloa*, *Erianthus*, *Frankenia*, *Glaux*, *Hyparrhenia*, *Ipomoea*, *Laguncularia*, *Limonium*, *Panicum*, *Paspalum*, *Paspalidium*, *Plumbago*, *Rhizophora*, *Reaumaria*, *Setaria*, *Sorghum*, *Sporobolus*, *Sonneratia*, *Saccharum*, *Statice*, *Tamarix*, *Tetrachne*, *Tetrapogon* and *Tricholaena*. Breckle (1995) classified the species with salt glands as **exo-recretohalophytes** while those with bladder cells (e.g. *Dorotheanthus*, *Mesembryanthemum*, *Atriplex*, *Chenopodium*, *Halimione* and *Salsola*) as **endo-recretohalophytes**. Reimann and Breckle (1988) observed bladder hair in *Chenopodium album* having a gland like short stalk cell, while in *C. murale*, the bladder is with several slender and vacuolized stalk cells. The essential role of the bladders is stated to be protection of young developing shoots and leaves from toxic levels first in the apoplast and subsequently in the symplast. In bladder hairs the secretion of salt primarily is not outside the plant body. The salt fluid is collected in a huge vacuole. This indicates to play a vital role in developing leaves to keep meristematic tissues low in salt. It demonstrates that *Atriplex* has rather efficient bladders in comparison to *Chenopodium*, where the bladders partly may have lost their ability to sequester salts. The efficiency of salt secretion to bladder vacuoles is dependent further more on salinity stress. Under high salinities the accumulation ratio is high, while under low salinity, the bladders are capable of even higher accumulation ratios. Many structural changes such as increase in succulence, changes in number and size of stomata, thickening of the cuticle, inhibition of differentiation, extensive development of tyloses, earlier occurrence of lignification changes in diameter and number of xylem vessels, stunting of growth, reduction in leaf size and sunken stomata may be ascribed to salinity which have been dealt with special reference to mangroves of Andaman and Nicobar Islands by Dagar et al. (1991).

Mangroves show following special adaptations related to root systems and development of seedlings. The substratum of mangroves is usually muddy, and anaerobic conditions are created. Therefore, many mangrove species have additional aerial roots or special kind of roots to facilitate the transfer of gases. The roots may be categorized into the following main types (Dagar et al. 1991):

(a) *Strut and stilt roots*: Species of *Rhizophora* and *Pandanus.*
(b) *Aerial prop roots*: All the species of *Rhizophora.*
(c) *Pneumatophores*: *Sonneratia* and *Avicennia* species produce numerous negative geotropic roots which rise vertically above the soil substratum from the underground cable roots. These are conical in *Sonneratia*, pencil-like in *Avicennia* and very thick gradually pointing upward and attaining up to 50 cm height in *Xylocarpus moluccensis*. These possess numerous lenticels. The absorbing roots move horizontally after rising from the base of pneumatophores in soil and bear numerous fibrous roots and hair. The horizontal cable roots also bear positive geotropic anchoring roots.
(d) *Knee roots*: In *Bruguiera*, *Ceriops* and *Heritiera fomes* lateral roots bend upward and come above the surface of the soil forming knee-like *pneumatophores* which are exposed kinks in the cable root system. These are stouter and thicker in *Bruguiera* and thinner and smaller forming loops in *Ceriops*.
(e) *Simple curved roots*: In *Lumnitzera* simple roots emerge above the soil surface and curve down below again but do not form thick knees. These produce absorbing roots beneath the soil surface.
(f) *Aerial flanges or planks*: Species of *Heritiera* and *Xylocarpus* have aerial flanges or planks on their cable roots involving the entire horizontal root becoming compressed vertically. Sometimes these planks travel several metres and form several partitions around trunk trapping sand or soil which otherwise will flow with water.
(g) *Buttresses*: At the base of the stem of many mangroves especially in *Bruguiera*, *Heritiera* and C*eriops* laterally compressed and flattened plank like buttresses are formed which give support to the tree and shelter to a variety of wildlife.

Development of Seedlings/Vivipary in Mangroves Many mangrove species are viviparous in their mode of seed germination, i.e. the seed germinates, while flower stalk is still attached to the parent. *Aegiceras corniculatum*, *Avicennia marina* and all species of family Rhizophoraceae show this character. The germinating radicles when fall in seawater floats and when gets the suitable substratum, immediately initiate rooting and establish. Propagules when floating in seawater of low salinity (due to mixing of freshwater from upstream near estuaries) exhibit significantly enhanced shoot and root growth compared with those in higher salinities. This phenomenon of viviparity is unique in mangroves which flourish in consistent tidal zone. It has been also found that very young seedlings of *Rhizophora* collected directly from the mother plant could also produce roots when grown in diluted seawater. Vivipary represents only a short and temporary stage of embryonic development prior to protrusion of the hypocotyl during which the embryo obtains the necessary nutrients for growth from the reserves in the endosperm. Once this source is exhausted, a shunt to a nearly heterotrophic "parasite" stage in which the embryo utilizes assimilation products supplied by the parent plant occurs. Under normal conditions only one seedling emerges while still attached to the fruit stock and protrudes down to varied lengths. During field surveys in Andaman and Nicobar Islands, unusual cases of multiple viviparity were observed in *Bruguiera cylindrica*, *B. gymnorrhiza*, *B. parviflora*, *B. sexangula*, *Rhizophora apiculata*, *R. mucronata* and *R. stylosa* (Dagar 1987; Dagar and Sharma 1989). Rao et al. (1986) also observed multiple viviparity in *B. gymnorrhiza*, *R. mucronata* and *Kandelia candel*. The ovary of *Bruguiera*, *Rhizophora* and *Kandelia* is bilocular to tetra-locular with one or two pendulous ovules in each locule, bilocular with two ovules and one locule with six ovules, respectively. The ovary is inferior in each case. Among the ovules all but one is suppressed under normal conditions which give rise to the embryo. In a few cases as mentioned above, one ovule from each locule when the ovary is bilocular or two ovules when unilocular emerge simultaneously in a viviparous manner. This unusual multiplicity of seedlings from a single fruit is intriguing. Whether this is under genetic control or under environmental stress is so far not clear.

5.6.2 Adaptations Related to Seed Morphology and Seed Bank

The seeds of many halophytes have evolved mechanisms of dormancy, either innate or enforced, that prevents their seeds from germinating under highly saline conditions (Ungar 1991, 1994). High soil salinities also inhibit seed germination in most halophytes and root growth in mangrove seedlings. A number of plant species growing in saline environments are found to develop some form of seed dimorphism or polymorphism. It is a common feature for adaptation which includes production of seeds different in size, seed coat pattern, weight, dormancies and germination requirements. Mohammed and Sen (1988) observed the occurrence of polymorphism in seeds of *Trianthema triquetra* while collecting seeds from Jodhpur, Pachpadra and Didwana localities. The latter two localities represent extreme saline areas. The seeds collected from the above three localities differed in seed coat pattern, weight, size, viability and germination behaviour. The seeds of Jodhpur and Didwana were, respectively, black and deep black in colour, while of Pachpadra they were light black. The seeds of Didwana were heaviest and of Pachpadra the lightest. The germination study revealed that the seeds from Jodhpur, Pachpadra and Didwana exhibited hard seed coat dormancies and only 8.8%, 48.7% and 35% seeds germinated from three respective localities. The viability of seeds was also different (50, 80 and 70%, respectively) at the three sites. Dagar et al. (2004b) classified seeds of *Salvadora persica* and *Jatropha curcas* into seven categories based on their weight and found clear gradation in their germination and lighter seeds had lower seed germination as compared to heavier seeds. Two types of seeds were also observed in sedge *Cyperus rotundus* where the heavier seeds showed a better germination than the lighter seeds. A number of annuals in the family Chenopodiaceae have developed forms of seed polymorphism which effects both the special and temporal distribution of seeds (Ungar 1987). The germination behaviour of *Salicornia europaea* with small seeds is more dormant and less salt-tolerant than large seeds.

Because of salinity stress and the unpredictable nature of most saline environments, a portion of the seeds produced may not germinate under hypersaline soil conditions. When the soil conditions are unfavourable and beyond the tolerance limits of species, non-germinated seeds may remain in the soil and serve as a transient or persistent seed bank. The seeds can remain stored in the soil for various lengths of time and then germinate later when the hypersaline conditions are alleviated. Investigations in a number of saline habitats (Ungar 1995) indicate that the importance of seed bank in salt marsh and salt desert vegetation varies considerably in the different localities. In inland saline environments where hypersaline conditions occur frequently, seed banks may be large and play a significant role in determining both the spatial and temporal distribution of species. However, in tidal coastal salt marsh habitats, the results have been less clear, with some plant communities having large persistent seed banks and others containing very few seeds in the seed bank. The degree of salinity stress in the habitat may be the determining factor as to the magnitude of the seed bank. The significance of seed banks is species dependent, with some perennial species in a given salt marsh habitat producing a persistent seed bank, while others do not. A number of annual halophytic species have been reported to produce persistent seed banks. Since annuals have only one opportunity to reproduce in their life history, seed banks may play a more significant role for these species than for longer-lived perennials.

Halophytes may resist stress by avoidance mechanisms. Seed banks are one of such mechanisms that delays seed germination to a favourable time during the year. Transitory seed banks are usually produced by enforced or induced dormancy and carry seeds over a predictable cold, dry or hypersaline period after which germination occurs. Persistent seed banks may serve as a longer-term seed-storage mechanism that allows seeds to remain in the soil over a period of months or years until favourable conditions for germination occur. Coastal communities of *Cressa cretica* maintained a persistent seed banks and peaked to 2800 seeds m^{-2} during May (Aziz and Khan 1995). The salt marshes and salt desert habitats are generally exposed to erratic precipitation patterns in many parts of the globe. In these habitats an adaptation to increased level of salinity has evolved at the germination stage that permits

Table 5.7 Seed bank of salt marsh and salt desert communities

Community	Type	Number of seeds per m^2
Armeria-Plantago	Salt marsh	4563
Atriplex griffithii	Salt desert	2000
Halimione portulacoides	Salt marsh	1040
Juncus gerardii	Salt marsh	130,000
Spartina patens	Salt marsh	470
S. alternifolia	Salt marsh	42
Spartina-Juncus	Salt marsh	1695
Salicornia europaea	Salt marsh	4318
S. virginica	Salt marsh	700
Suaeda fruticosa	Salt desert	1001
S. vera	Salt marsh	20,494
Suaeda-Salicornia	Salt marsh	7696
Salicornia-Hordeum	Salt marsh	479,200
Spergularia marina	Salt marsh	471,135
Atriplex triangularis	Salt marsh	108,280
Phragmites australis	Salt marsh	1400
Scirpus maritimus	Salt marsh	2194
Distichlis spicata	Salt marsh	850

Source: Ungar (1995)

seeds to remain dormant during these stress periods. Ungar (1995) reviewed seed bank data of some salt marsh and desert communities (Table 5.7).

5.6.3 Seed Germination Behaviour for Saline Adaptation

In saline environments, halophytes have evolved a number of seed germination mechanisms. These range from producing viviparous seedlings in many mangroves, producing non-dormant seeds (e.g. *Salvadora persica*), to the production of seeds with persistent or transient levels of dormancy. Seeds of *Salvadora persica*, *S. oleoides* and *Azadirachta indica* show almost negligible dormancy. These germinate just after when placed in moisture. The fruiting in these species occurs just in the peak of summer, and as soon as the first shower comes, the seeds germinate immediately when the salinity of surface soil is leached down. Halophytes are exposed to a number of different kinds of stress in salt marsh, mangrove and salt desert environments. A partial list of these includes osmotic stress, specific ion toxicities, nutrient deficiencies and anaerobic conditions due to tidal flooding and the presence of shallow water tables (Adam 1990; Ungar 1991).

The information regarding germination behaviour of the Indian halophytes is sparse. In field conditions the highest germination percentage in *Cressa cretica*, *Haloxylon recurvum*, *Suaeda fruticosa* and *Trianthema triquetra* could be achieved after rains which helped the salts to leach out from the close environment of the seeds. While comparing the seed germination in eight species, Sen et al. (1982) found that germination was better in *Salsola baryosma* in low osmotic potentials, because seeds could germinate up to osmotica of −13 bars. Increase in germination was seen in *Salsola baryosma*, *Sesuvium sesuvioides* and *Trianthema triquetra* with a slight decrease in osmotic potentials up to −1 or – 2 bars. Only *Cressa cretica*, *Salsola baryosma*, *Sporobolus helvolus* and *T. triquetra* could germinate to a certain extent under osmotic stress of −7 bars, whereas *S. baryosma* showed germination even in −9 bars. Rao et al. (1999a, b) and Dagar et al. (2004a, b, c, 2005, 2009) studied seed germination behaviour in some halophytes and found that in many cases more salts get accumulated in bark and leaves and these organs act as potential sink for toxic ions such as sodium and chloride.

Seeds of some halophytes show unique behaviour in their adaptations towards the salinity. Williams (1960) reported that the black seeds of *Halogeton glomeratus* raised on moist filter paper absorbed water so rapidly that the seed coat ruptures and the embryo are expelled within an hour. The germination in the seeds of *Haloxylon recurvum* and *H. salicornicum* commonly occurs within an hour (Sharma and Sen 1989). The time taken for seeds to imbibe water and the embryo to emerge from the seed coat was studied in these two species. It could be observed that the percentage of water imbibition rapidly increased with increase in the duration of hydration and reached a maximum after 150 and 90 min in *H. recurvum* and *H. salicornicum*, respectively. The seed germination in *H. recurvum* initiated within 75–120 min in April and 25–80 min in May, whereas in *H. salicornicum* this period was 40–180 min in April and 60–120 min in May. The initiation was fastest during 3–5 p.m.

In mangroves, *s*pecies such as *Nypa fruticans* and *Phoenix paludosa* and littoral grasses like *Aeluropus lagopoides*, *Porteresia (Oryza) coarctata* and *Myriostachya wightiana* may propagate by vegetative means through underground propagules and avoid the dependence on seed production for their survival. The fern *Acrostichum aureum* becomes gregarious due to its capacity of propagation through root suckers. Its spores also germinate quickly on mud heaps mounded by fiddler crabs in tidal zones producing heart-shaped prothalli. Species like *Spartina patens* and *Salicornia europaea* are capable of germinating in seawater.

5.6.4 Physiological Traits

Salt-tolerant species have special physiological mechanisms to adapt to high saline environments, such as salt exclusion, intra-plant salt translocation (e.g. from sensitive shoots to older leaves or roots), cellular osmotic adjustment (e.g. dilution by increasing water uptake), salt intracellular compartmentation (e.g. accumulation in the spaces between cells) or salt excretion (e.g. through salt glands), that allow these halophytic species to cope with high salt concentrations in soil and water. Previous studies have primarily targeted external sequestration in salt bladders, internal Na^+ sequestration in vacuoles, stomatal aperture and density and xylem ion loading processes. Shabala (2013) indicated that there is nothing unique that halophytic possess that is not found in other crop species. Instead, halophytes are doing everything just "a bit better" and have a set of highly complementary and well-orchestrated mechanisms in place to deal with salinity stress.

Although there are many aspects of the physiology of salt tolerance that are yet to be understood, it is clear that the trait is complex in that, at a minimum, it requires the combination of several different traits: the accumulation and compartmentation of ions for osmotic adjustment, the synthesis of compatible solutes, the ability to accumulate essential nutrients (particularly K) in the presence of high concentrations of the ions generating salinity (Na), the ability to limit the entry of these saline ions into the transpiration stream and the ability to continue to regulate transpiration in the presence of high concentrations of Na^+ and Cl^- (Flowers and Colmer 2008).

5.6.5 Role of Organic Solutes in Salinity Adaptation

It is now generally accepted that compartmentation of Na and Cl ions is one of the physiological characteristics involved in salt resistance (Wyn Jones 1984; Yeo and Flowers 1989; Rao et al. 1999a, b; Dagar et al. 2004a, b, c 2005, 2009). While Na^+ and Cl^- are mainly sequestered within the vacuole, a high K^+ concentration (80–150 mol m^{-3}) has to be maintained in the cytoplasm in order to stabilize the ribosomes. However, the number of inorganic ions present in the cytoplasm does not suffice to balance all those stored in the vacuole. Therefore, nontoxic solutes are needed to serve for the intracellular osmotic adjustment between cytoplasm and vacuole (Popp and Albert 1995). The investigations on free amino acids in halophytes which occur in extremely saline milieus suggest that proline always occurs in large quantities. Joshi (1982) reported that proline varied from 20.54% to 82.87% (in winter) of total amino acids in three halophytes. The phenomenon of free proline accumulation in plants exposed to diverse environmental stresses has considerable ecophysiological significance. Proline has also been known to accumulate in the leaves of many plant species when subjected to low temperature, salt stress or even starvation (Chu et al. 1976). Further it was also observed that proline is not necessarily an indicator of stressed condition, and it was found that many well-adapted desert plants did not show any marked proline content in conditions of stress. Some plants showed high proline content in winter under cold stress, some accumulated proline in water-stressed conditions, and others in non-stressed conditions (Mohammed and Sen 1990). The proline accumulation was more in the tissues of plants which grow in higher saline habitats as compared to lesser saline habitats (Sen and Mohammed 1991; Dagar et al. 2009).

Several families showed preponderance for one of the groups of compatible solutes. For instance, in 28 out of 29 species of Chenopodiaceae compared by Popp and Albert (1995), quaternary ammonium compounds (QAC) were the prevailing organic osmolytes. Only in *Sarcobatus vermiculatus* cyclitols predominated. A closely related *Philoxerus vermicularis* also showed a high QAC content, whereas the family Aizoaceae which belongs to the same order of Caryophyllales stored cyclitols and proline in varying ratios. Other families, which showed changing contributions from QACs, proline and cyclitols, were the Asteraceae, Solanaceae, Plumbaginaceae and Zygophyllaceae. The cyclitol concentrations in woody *Prosopis juliflora* and *Pithecellobium dulce* (Mimosaceae) exceeded those of herbaceous members of Aizoaceae and Asteraceae. Comparing the concentration ranges of the organic solutes, Popp and Albert (1995) found that proline reached similar high levels like cyclitols in the Fabaceae, Brassicaceae and some of the Zygophyllaceae.

Within herbaceous halophytes, hexitols were reported by Popp and Albert (1995) in *Plantago maritima* (Plantaginaceae) and *Myoporum insulare* (Myoporaceae), while the picture in mangroves was found quite different. Most of the mangroves showed a clear preponderance for storage of polyols and acyclic as well as cyclic ones. Mannitol was found in *Aegiceras corniculatum*, *Scyphiphora hydrophyllacea*, and all members of *Combretaceae* and *Sonneratiaceae*. In Rhizophoraceae, 1D-I-O-methyl-muco-inositol was present, while *Excoecaria agallocha* accumulated quebrachitol. In addition to some proline, *Aegialitis annulata* accumulated quebrachitol and choline sulphate. In all species of *Avicennia*, glycine betaine was the dominating organic solute. Within the mangroves there were only two species (*Acanthus ilicifolius*, *Xylocarpus granatum*) which stored high amount of proline. It is also worth mentioning here that most of the mangroves contained higher amounts of compatible solutes than those needed to balance the inorganic ions assuming that the organic osmolytes are confined to the cytoplasm. In *Agrostis stolonifera* both salt and glycine betaine levels increased during the vegetation period, but in other species from the same site, neither the built-up of inorganic ions nor the accumulation of compatible solutes was that way, probably due to an increase in succulence which is also an effective mechanism in salt regulation (Popp and Albert 1995).

Development of anthocyanins is a well-known characteristic of plants exposed to drought, osmotic drought or physiological drought. Anthocyanins may develop in the leaves or stems of plants when a change in their metabolism results in a change in their ability to resist stress conditions. Some halophytes like *Suaeda fruticosa*, *S. nudiflora*, *Salsola baryosma*, *Arthrocnemum indicum*, *Trianthema triquetra* and *Zygophyllum simplex* exhibit the above characteristic under conditions of osmotic stress. However, it is difficult to assess why certain species accumulate certain types of compatible solutes. The common acting principle might be that all the substances mentioned above have no perturbing effects on protein structures as it is known for inorganic ions, which favour unfolding by entering the hydration sphere of proteins (Rhodes and Hanson 1993; Samaras et al. 1995). The stabilization of folded protein structures by compatible solutes and their compartmentation within the cell are decisive prerequisites for salinity adaptation (Popp and Albert 1995).

5.6.6 Impact of High Salts on Growth and Development of Halophytes

It is normally observed that halophytes can tolerate increased salinity but the increased salts from a critical range do reduce the growth and total biomass of most halophytes. Keiffer and Ungar (1997) reported that *Salicornia europaea* seedlings were maintained for 11 weeks under saline waterlogged conditions, whereas seedlings grown in nonsaline waterlogged conditions died in 6 weeks. These results showed that *Salicornia*, which is typically found in low marsh or inland salt marsh conditions, could not overcome the stress of being waterlogged in a freshwater environment. *Atriplex amnicola* was grown with water having different ratios of K to Na. The growth reduction was greater when the ratio of K/Na was 1:1 than when it was 1:100 (El-Haddad and O'Leary 1994). When four species of *Atriplex* (*A. amnicola*, *A. lentiformis*, *A. nummuloria*, *A. undulata*) were grown in alkali soil (pH 8.2, 9.2 and 10.0), it was found that the growth and biomass were maximum at pH 10 in all species. Phosphate increases the salt tolerance in some halophytes. Okusanya and Fawole (1985) found that salt tolerance increased in *Lavatera arborea* when phosphate was added to the soil. The potassium, calcium, magnesium and phosphorus contents in the shoot also increased when phosphate was added. It has normally been reported that enzymes from halophytes are as salt sensitive as from glycophytes. Shomer-Ilan et al. (1985) found that preconditioning as well as substrate concentration was a factor in making the halophyte enzyme phosphoenolpyruvate carboxylase more salt-tolerant. The addition of solutes such as betaine, proline or glycerol stabilized the enzyme (Shomer-Ilan and Waisel 1986). When low potassium was present in the in vitro halophyte protein synthesis system, sodium increased the production, whereas, when the potassium level was high, additional sodium decreased the production (Flowers and Dalmond 1992).

5.6.7 Toxicity of Excess Salt Ions

While the increased ion concentration permits halophytes to take up water from soils, there is a problem of the toxic effect of excess ion accumulation. Halophytes use several mechanisms to avoid the toxic effect of excessive ion accumulation (Weber 1995). Some of these mechanisms are discussed below.

Root Exclusion The exclusion of ions by roots can be a factor of salt tolerance, but some type of osmotic compound needs to be produced in the plant to continue to pull water from the saline soil. In manila grass and Bermuda grass, salt tolerance was found associated with exclusion of sodium and chloride ions from the shoots, a process aided by leaf salt glands. Glycine betaine and proline increased in the grass shoots as the level of salinity increased (Marcum and Murdoch 1992, 1994). Flowers (1985) and Flowers et al. (1986) stated that in dicot halophytes, root exclusion is not an effective mechanism, although there may be some ion regulation at the root level. Scholander (1968) described the presence of an ultrafilter in roots of mangroves of the family Rhizophoraceae, enabling only selective absorption of ions. They may retain a low internal salinity by means of salt-excluding mechanisms in the roots. In this type, sodium and chloride concentrations are higher in xylem sap and do not reach the metabolic cellular environment.

Salt Excretion The removal of high salt concentrations by excretion through salt glands is another method of reducing the excess ions in tissues. *Limonium* and

Distichlis are examples of halophytes with salt glands. In mangrove species of *Avicennia*, *Aegialitis*, *Aegiceras* and *Acanthus*, NaCl concentration in the excreted solution exceeds the NaCl concentration of seawater, and this is normally ten times that of salt exclusion type and also does not reach the metabolic environment (Joshi et al. 1975). The same holds true for *Aeluropus lagopoides*, *Limonium latifolium* and *Tamarix articulata*. This regulation is maintained by salt glands which are assumed to transport and excrete ions against a concentration gradient. Liphschitz and Waisel (1982) explained in detail the following facts that the ionic excretion of salt glands is constituted mainly of sodium and chloride; the relationship between the excreted sodium and chloride varies with the time of exposure of the plants to the salt solution; under high temperature (in the range of 25 to 30 °C) conditions, the excretion rates are usually accelerated; excretion process is light dependent; the diurnal variation in salt excretion was highest in noon (in mangroves *Aegialitis* and *Aegiceras*); low concentrations of metabolic inhibitors (KCN, Na azide, NaF, arsenite, DNP) stimulated slightly the chloride excretion and inhibition takes place when their concentration is above 5×10^{-3} M; and the excretion of salts by salt glands is an active process.

Salt Accumulation and Succulence Mangrove species of *Sonneratia*, *Lumnitzera* and *Excoecaria* have been found to have excessive number of ions in their organs and thus absorb and accumulate ions, and their leaves become fleshy. Halophytes such as *Suaeda* and *Salicornia* also have succulent leaves and stems. The development of succulence results in a dilution effect on the salt concentration in tissues and increases the salt tolerance of the plants. Succulence also results in a range of anatomical and ultrastructural features such as increased leaf cell size (Flowers et al. 1986). Among mangroves salt-accumulating species are least dominant contrary to the salt-excreting species which are most dominant. The latter are more predominant towards sea (Dagar et al. 1991; Dagar 2008).

5.6.8 Genetic Basis of Salt Tolerance

The genetic basis for salt tolerance is complex, and the potential for characterizing genes relating to salt tolerance is increasing with the availability of the molecular biological tools. Vogelien et al. (1993) while comparing two mutations of *Ceratopteris richardii* (st II and st 12) which conferred low and high levels of NaCl tolerance suggested that the tolerance was associated with altered ion accumulation during NaCl stress rather than an enhanced ability to accumulate organic solutes for osmotic adjustment of the cytoplasm. Dubcovsky et al. (1994) compared genes that showed enhanced mRNA accumulation in the early stages of salt stress in *Lophopyrum elongatum*. Andolfatto et al. (1994) used *Agrobacterium rhizogenes* to transform the normal roots of *Mesembryanthemum crystallinum* into hairy roots, and the transformed hairy roots caused an eightfold increase in the proline level in the tissues. They conserved the several responses to salt tolerance between the two types of roots. Glenn et al. (1994) compared two subspecies of *Atriplex canescens* and suggested that the breeding for sodium accumulation rather than exclusion may be a more effective strategy for improving salt tolerance of plants. Thus, the modification of crop plants by genetic engineering is also becoming a possibility.

Breckle (1995) was of the opinion that the various structures and processes or functions of plants which are affected by salt should be regarded simultaneously. As the selectivity to species ions play a very important role in adaptation of halophytes, this is a typical feature of membranes in all organs, starting with the rhizodermis and ending with the leaf surface. All functional organelles are affected by salts, and often the membranes keep the salt level in the various organelles low by active pumping of ions to the vacuole, whereas osmotic adjustment is reached by compatible solutes as, for example, cyclitols in the cytosol (Breckle 1995). Cells, tissues and organs have to be in functional cooperation to cope with excessive salt.

In the earlier times, the entire plants were often investigated for their salt tolerance, and only recently the concept at cell or gene level has gained importance. From the ecological viewpoint, the saline ecotypes, and thus the halophytic ecosystems, are very specific systems. They are often characterized by a high turnover of salt (NaCl). Thus, within the ecosystem, salt cycling plays a major role which may predominantly be caused by specific desalting structures on the leaves of halophytes, more general also by uptake of salts from the soil and leaf shedding and leaf turnover of salt-tolerant plant species. Thus, the pools of NaCl in ecosystem components and fluxes of ions between ecosystem components may be totally different in saline habitats from nonsaline ones.

Following ecophysiological approach, which takes the salt uptake and fate of the salt within the plant body as a guideline, Breckle (1995) referred the plants, which are very selective with their root cell membranes and thus can exclude the great majority of NaCl from being uptaken, as non-halophytes. There are plant species which can withstand higher salinities without having any special adaptations, besides a very good selectivity at their root membranes and in the other plant tissues. More often they tend to accumulate salt in the roots and the lower shoot parts (xylem parenchyma). These plants were grouped as pseudo-halophytes. A higher uptake of salts and transport to the shoot can be observed with the halosucculent eu-halophytes. Either the leaves or the stems or both become succulent. The eu-halophytes are the classical plants on high saline stands. These are halophytes of another type which exhibit elimination of salt by special structures on the aerial organs like salt glands and bladder hairs. This elimination has been called recretion (Breckle 1995), since NaCl went through the plant body chemically unchanged. The angiospermic genera with salt glands (exo-recretohalophytes) include *Acanthus*, *Avicennia*, *Aegiceras*, *Aegialitis*, *Armeria*, *Andropogon*, *Bouteloua*, *Buchloe*, *Brachiaria*, *Convolvulus*, *Chloris*, *Coix*, *Cynodon*, *Coelocaryon*, *Crypsis*, *Cenchrus*, *Chrysopogon*, *Cordylanthus*, *Castilleja*, *Distichlis*, *Dactyloctenium*, *Dinebra*, *Dichanthium*, *Digitaria*, *Eleusine*, *Enteropogon*, *Echinochloa*, *Erianthus*, *Frankenia*, *Glaux*, *Hyparrhenia*, *Ipomoea*, *Limoniastrum*, *Limonium*, *Myricaria*, *Panicum*, *Paspalum*, *Paspalidium*, *Reaumaria*, *Saccharum*, *Setaria*, *Sorghum*, *Tricholaena*, *Tetrachne*, *Tetrapogon* and *Tamarix*, while those with bladder cells (endo-recretohalophytes) include *Atriplex*, *Chenopodium*, *Dorotheanthus*, *Halimione* and *Salsola* (Breckle 1995).

The information given above regarding adaptations is incomplete because of the reasons that it is very difficult to tackle all aspects of such a complex subject, and several processes and interrelations are not yet understood. Uptake of minerals and selectivity is enhanced in some halophytes; thus, the membrane structures may be different. Ion interrelations play a major role in ion uptake. Hormonal balance and growth regulation is an important factor in adaptation to stress, but the physiological and biochemical level has still to reply many open questions. The utility of halophytes in transferring of salt-tolerant genes or breeding the crops from natural halophytes may open new vistas. The other way of utilization of degraded salt lands is using natural halophytes, which already have set of halophytic genes and are certainly more promising for breeding salt-resistant crops.

5.7 Using Indicator Plant Lists

The variation in soil and climatic conditions influences the different vegetation communities. Within each vegetation community, there are some plants that are tolerant to salinity or waterlogging or a combination of these conditions. This tolerance will change with the growth stage and general well-being of the plant species. Thus, it is preferable to use indicator species lists that are specific to an area in combination with other site investigation techniques along with local knowledge.

Preference to botanical names should be used rather than common names while referring to individual plants as sometimes confusion may arise when there are several common names for the one species or when the same common name is used for more than one plant. For example, *Sporobolus virginicus*, a common grass species of salt marsh areas along the coast of West India and coastal region of Australia, is commonly called saltwater couch or sand couch. Those unfamiliar with this plant may confuse this species with the couch that is commonly used as turf grass, *Cynodon dactylon*, which is also known as couch, common couch or coastal Bermuda grass. Likewise, *Juncus acutus* is a plant species that is commonly known in some areas as spiny rush and in other areas as spike rush.

Some indicator plant lists also include an indication of salt tolerance ranges for the different plants. Different environmental factors, variations in testing procedure, variations within species, test methods and the use of laboratory or field studies may influence the test outcomes. For example, the species found to be salt-tolerant in the laboratory might not be tolerant of similar salinity levels in the field. Therefore, it is important to equate the conditions under which the salt tolerance testing was done while using tolerance ranges as an indication of site conditions or for re-vegetation purposes.

Plant Roots
The plant root is an important organ of plant that comes in direct contact with the soil solution, thus being the first to encounter the saline medium (Bernstein and Kafkafi 2002). The root distribution pattern in soil is reflection of the plant ecological adaptation and may increase a chance of plant survival under salt stress (Hartlea et al. 2006). However, root responses to soil salinity in halophytes and their relation with plant growth are poorly understood (Yang et al. 2016). Among mangroves, some root mechanism is interesting, for example, pneumatophores (*Avicennia* and *Sonneratia*) show negative geotropism bearing anchor lateral roots having function of absorption, while the hanging prop roots (*Rhizophora*) are positively geotropic, and when the muddy substratum is touched, these do anchor and also develop absorption roots.

5.8 Halotolerant Microbiome as Indicators

There are soil microbes (especially rhizosphere bacteria and mycorrhizal fungi) that interact with plants by alleviating salt stress. Many species of halotolerant microbes have been isolated and identified (Trivedi 2017) such as *Azotobacter*, *Azospirillum*, Phosphobacter and blue-green algae from marine aquatic sediments. The bacterial sequences were assigned into 5784 operational taxonomic units (OTUs, based on $\geq$97% sequence identity), representing 24 known bacterial phyla, with *Proteobacteria* (44.9%), *Actinobacteria* (12.3%), *Firmicutes* (10.4%), *Acidobacteria* (9.0%), *Bacteroidetes* (6.8%) and *Chloroflexi* (5.9%) being predominant. The dominant bacterial genus in saline soils is *Lysobacter* (12.8%), followed by *Sphingomonas* (4.5%), *Halomonas* (2.5%) and *Gemmatimonas* (2.5%). Archaeal sequences were assigned to 602 OTUs, mainly from the phyla Euryarchaeota (88.7%) and Crenarchaeota (11.3%). The dominant archaeal genera in saline soils are *Halorubrum* and *Thermofilum*. Rarefaction analysis indicated less than 25% of bacterial diversity and approximately 50% of archaeal diversity, in saline soil (Trivedi 2017). Also, halophilic endophytic microbes dominate the leaves of the halophytes and salt-tolerant plant species (Arora et al. 2013, 2014b).

Rhizobium symbiosis is more sensitive to salt stresses than free-living rhizobia (Trivedi and Arora 2013). *Rhizobium* spp. can support up to 500 mM NaCl which discovered a leg for certain types of rhizobia adapted to saline conditions by the intracellular accumulation of organic solutes of low molecular weight called osmolytes, glutamate, trehalose, glycine betaine and multi-amine or the accumulation of K^+.

Salinity and water deficiency disrupt photosynthesis process and increase photorespiration, altering the normal homeostasis of cells and causing an increased production of reactive oxygen species (ROS) such as the super oxide radical, hydrogen peroxide and hydroxyl radical (Miller et al. 2010). ROS are mainly produced at low level in organelles such as chloroplasts, mitochondria and peroxisome under optimal growth conditions. During stress, the enhanced production of

ROS can pose a threat to cells, but it is thought that ROS also act as signals for the activation of stress response and defence pathways.

Plants have some common adaptation mechanisms when exposed to environmental stresses, such as extremes of temperature, high salinity, drought and nutrient deficiency or toxicity of heavy metal, including changes in root morphology, a process in which phytohormones are known to play a key role. The majority of root-associated bacteria that display beneficial effects on plant growth produce indole-3-acetic acid (IAA), and this bacterial production of IAA also stimulates the activity of enzyme 1-aminocyclopropane-1-carboxylate (ACC) deaminase that is involved in the degradation of the ethylene precursor ACC. Activity of ACC deaminase could be helpful in sustaining plant growth and development under stress conditions by reducing stress-induced ethylene production. Modulation of other major plant hormones could improve salt tolerance in crop plants by reducing the toxic effects of salinity. Numerous nitrogen-containing compounds accumulate in plants exposed to saline stress. The most frequently reported modification induced by salt stress as well as other stresses in plants is accumulation of the amino acid proline. *Medicago* plants infected by IAA-overproducing PGPR strains are able to overcome different stressful environmental conditions and accumulate high levels of proline. This has been confirmed by increased expression levels of two genes involved in the first two steps of proline biosynthesis from glutamic acid.

To adapt to osmotic stress, microorganisms employ two strategies which were described by Killham (1994). Both of these strategies result in an accumulation of solutes in the cell to counteract the increase in osmotic pressure. The first strategy is the selective exclusion of the solute incorporated (e.g. Na^+, Cl^-), thus accumulating the ions necessary for metabolism (e.g. NH_4^+). The other possible cell adaptation mechanism is the production of organic compounds that will antagonize the concentration difference between the soil solution and the cell cytoplasm. This adaptation finally results in a physiologically more active microbial community and, in consequence, reduced substrate use efficiency (Arora and Vanza 2017).

These mechanisms are, however, known for single microorganisms, but little has been studied at the community level. While sensitive cells are damaged by the low osmotic potential, some microorganisms can adapt by accumulating osmolytes (including amino acids in bacteria while polyols in fungi) that help retain water (Oren 2001; Hagemann 2011; Beales 2004). The synthesis of osmolytes requires large amounts of energy, 30 to 110 ATPs, when compared to the energy of 30 ATPs required to synthesize the cell wall (Oren 1999), thus, representing a significant metabolic responsibility for the microorganisms, and reduces the energy available for the plant growth. The major part of soil biochemical transformations is dependent on or normally related to the presence of enzymes; an evaluation of their activities could be useful to indicate if a soil is adequately carrying out the processes closely connected to its quality.

5.8.1 Microbial Enzyme Activity

Plant growth is affected by soil enzymatic activity and soil microorganisms. The enzymes are secreted by microorganisms, plants and soil fauna, and they regulate many of the soil biological processes (Gunnarsson et al. 2014). Soil microorganisms are recognized as a key factor influencing plant growth, but it is very challenging to characterize soil microbial communities fully. In particular, there is little knowledge about the structure of microbial communities in the rhizosphere of halophyte plant species growing in salt-affected soils. Amid the diverse soil enzymes, dehydrogenase, β-glucosidase, urease and the phosphatases are important in the transformation of different nutrients for plants. The activity of dehydrogenase reflects the total oxidative capacity of the microbial biomass (Nannipieri et al. 1990) and is involved in the central aspect of metabolism. Another enzyme β-glucosidase is an important enzyme in the land carbon cycle, in the production of glucose, which constitutes a key energy source for the microbial biomass. Thus, the determination of β-glucosidase activity, among other hydrolytic enzyme activities, has been recommended as a good indicator of soil quality. The phosphatases play an important role in the transformation of organic phosphate into inorganic forms more appropriate for plants.

Soil enzymatic activity is negatively influenced due to salinity, although the degree of inhibition varied according to the enzyme analysed and the nature and amount of salt in soil. Soil dehydrogenase activity was severely inhibited, whereas the hydrolases showed a milder degree of inhibition. Reduction of enzyme activity in saline soils may be due to the osmotic dehydration of the microbial cells that release intracellular enzymes, which become susceptible to the attack by soil proteases, with a resultant decrease in enzyme activity. The salting-out effect modifies the ionic conformation of the protein-enzyme active site. Similarly, the specific ionic toxicity causes a nutritional imbalance for microbial growth and subsequent enzyme synthesis.

It has also been noted that an increase in soil salinity inhibited the enzyme activities of benzoyl argininamide alkaline phosphatase and β-glucosidase and also microbial respiration. Activities of enzymes invertase and urease were also severely reduced by an increasing concentration of sodium chloride (NaCl) during incubation. In addition, the nitrate reductase was inhibited in the majority of the treatments. While comparing the enzyme activities of saline soil with those of normal soil, it has also been observed to decline in amylase, catalase, phosphatase and urease activities with increasing salinity. The microbial and biochemical parameters were adversely affected by the salinity, and the most extreme situation occurred during the summers. The activity of dehydrogenase was the most affected.

There are many salinity indicators which include soil, water, inland and coastal plants and their associate microbes which are governed by several environmental, biochemical and physiological parameters which in turn control the adaptations. Though much information has been generated, still there exist a lot of gaps, and much more research is needed particularly in the fields of ecophysiology, soil metagenomics and transgenic research which may lead to develop more and more new salt-tolerant crops for their domestication to solve the food and other requirements of ever-increasing population and identify useful halophilic microbes to alleviate stress.

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Soil-Plant-Microbe Interactions in Salt-affected Soils

6

Madhu Choudhary, Priyanka Chandra, and Sanjay Arora

Abstract

Soil salinization is a major abiotic constraint which causes loss of productivity of cultivated soils. Salinity affects plant growth by reduction in osmotic potential, imbalance of nutrients, and ion toxicity. Microorganisms have the ability to tolerate or adapt stresses; like under salt stress conditions, they synthesize osmolytes which help them to maintain cell turgor and metabolism. Halophilic plant growth-promoting microbes have been considered to mitigate such environmental stress. These have the multiple mechanisms, such as production of indoleacetic acid, ACC (1-Aminocyclopropane-1-Carboxylate) deaminase, exopolysaccaride, and siderophore, phosphate solubilization, and nitrogen fixation and have antifungal activity, which makes them play important role in plant growth promotion under salt stress. Mycorrhizal fungi demonstrate several plant growth promotion properties by several mechanisms. These mechanisms include production of several plant growth-promoting metabolites like amino acids, vitamins, and phytohormones. Mycorrhiza also has the nutrient solubilizing and mineralizing potential, thus, can enhance plant tolerance against salinity and other environmental stresses. Many halophilic plant growth-promoting microbes and their consortia have recently been used for the promotion of plant growth under salt stress conditions and their bio-formulations acts as eco-friendly and cheap strategy for amelioration of salt-affected soils.

Keywords

Salinity · Halophilic microbes · Plant growth promoters · ACC deaminase · Mycorrhiza

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6.1 Introduction

The increasing human population is the most severe problem of the time, and to feed this ever-growing population it is necessary to utilize every inch of land. But due to the various environmental stresses (soil salinity, climate change, uneven rainfall, drought, flooding, and extreme temperatures), available land for cultivation is shrinking, causing threat for agricultural sustainability. It is estimated that every year 10 million ha agricultural land is severely affected by salt accumulation (Pimentel et al. 2004). It is estimated that by 2050, the world population is estimated to reach at 8.9 billion from the current 7 billion (UN report 2017), while salt-affected area will be reached to 50% of the world's arable land (Bartels and Sunkar 2005). Increasing soil salinization is recognized as an obstacle to accomplishing the goals of sustainable agricultural production. Salinity is a well-known limiting factor that affects plant growth and development.

High salt concentrations lead to reduction in the photosynthetic rate and the enzymatic activities which resulted reduction in crop yields (Lee et al. 2013). Salt increases soil osmotic pressure and interferes with plant nutrition which resulted into stunted plant growth. High concentration of salt in soil solution turns down the ability of plants to take up water, and this can be referred to as the water-deficit or osmotic effect of salinity. The osmotic effect induces metabolic changes in the plant identical to those caused under water stress conditions (Munns et al. 2002). Ion-specific toxicities and nutritional imbalances caused by salt stress also resulted in reducing plant growth (Läuchli and Epstein 1990). Excessive amounts of salt can enter in the transpiration stream of plants where they can injure cells of the leaves, and this may cause growth reductions. This is called the salt-specific or ion-excess effect of salinity (Greenway and Munns 1980). Despite negative effect of salts on plant growth, some plants can grow well in salt-affected soils. The salt tolerance in a plant is a result of interactions among plant physiology, genetic constitution, and climate, which affects adaptability of plants in such situations. The sensitivity of plant roots varies widely with plant species. Most of the major field crops are good to medium salt tolerant, and some are high salt tolerant. Medium salt-tolerant crops include most of the cereal crops like wheat, oats, and rice. High salt-tolerant crops are barley, sugar beet, and cotton, while maize and sorghum are usually considered to be more sensitive to salt than the other cereals (Hayward and Bernstein 1958).

Many strategies like use of chemical amendments, subsurface drainage, and salt-tolerant varieties are adopted to mitigate salt stress and to boost the crop productivity. One of the strategies that is based on biological method and has been considered to mitigate such type of environmental stressors is use of plant growth-promoting microbes (PGPMs). Directly or indirectly these can enhance plant performance under stress conditions and subsequently enhance yield (Dimkpa et al. 2009). The direct effect of PGPM includes an increase in synthesis of plant hormones, availability of nutrients, and nitrogen fixation (Hayat et al. 2010). The indirect effect includes protection of the plants against soil-borne diseases. Worldwide researches have shown that diverse group of root-associated microorganisms have potential for promoting plant adaptations to salt stress (Siddikee et al. 2010, 2011). Under abiotic stresses like salinity and drought, plant produces high level of ethylene; this retards plant growth and causes plant senescence. PGPMs have the ability to produce ACC deaminase, which catalyzes the conversion of ACC (a precursor of ethylene biosynthesis) to ammonia and α-ketobutyrate. Thus, ACC (1-Aminocyclopropane-1-Carboxylate) deaminase reduces levels of ethylene which would finally overcome the salt-induced growth inhibition in plants.

6.2 Effect of Soil Salinity on Growth and Development of Plants

Across the globe soil salinity is a major threat for plant growth and development (Rui et al. 2009). Salts like NaCl, $MgCl_2$, KCl, Na_2SO_4, $MgSO_4$, $CaSO_4$, and Na_2CO_3 are responsible for salinity, but it has been reported that among them NaCl is the one of the major salts to cause salinity problem in soil (Munns and Tester 2008). Salinity affects plant growth by reduction in osmotic potential, nutrient imbalance, and ion toxicity. High salt concentrations in soils negatively affect physiological aspects of plants like osmotic balance, stomata closure, cell division, and photosynthesis (Lee et al. 2004; Wang et al. 2012). Adverse conditions like salinity cause reduction in the photosynthetic area by premature senescence of leaves. High salt concentrations also affect genetic aspects, such as synthesis of protein and regulation of gene in plants (Siddiqui et al. 2012). High salinity causes decrease in CO_2 availability and reduction of the contents of photosynthetic pigments hence affects photosynthesis (Flexas et al. 2007; Ashraf and Harris 2013). As a result of physiological and genetic changes, morphological changes like reduced size of leaves and presence of salt glands also occur. Accumulation of Na^+ and Cl^- in the tissues of transpiring leaves causes cell damage, inactivates enzymes, and also leads to inhibition of protein synthesis (Taiz and Zeiger 2002). Accumulation of salt in the root zone causes nutrient imbalance and osmotic stress by disturbing cell ion homeostasis, inducing ion competition by the accumulation of Na^+ and Cl^-, and inhibition in uptake of essential elements such as K^+, Ca^{2+}, and NO_3^- (Wang et al. 2003; Munns and Tester 2008; Singh et al. 2014; Liu et al. 2015). This results into the reduction of plant growth and ultimately lower productivity (James et al. 2011). It also adversely affects the other metabolic processes by decreasing the ability of plant to take up water. Both the ions Na^+ and K^+ have same hydrated ionic radii; thus they can enter from the same entry site which can cause ionic disturbance and result in deleterious effects on protein biosynthesis and enzyme activation (Wang et al. 2013). These effects are more prominent in older leaves, as they have been transpiring the longest so they accumulate more ions (Munns et al. 2002). Several studies have suggested that for photosynthesis and overall plant growth, low Na^+/K^+ ratio is required in the plant cells to maintain ionic homeostasis under salinity stress condition (Cuin et al. 2003; Rodrigues et al. 2013). In comparison to the Cl^-, the toxicity caused by Na^+ is more severe because uptake of Na^+ is easier than Cl^-. The Cl^- can enter into the plant cell only when the concentration of Cl^- is low in cell cytosol. The concentration above the permissible limit leads to the problem of salt stress. Under such condition plants adapt a number of strategies to counteract damaging effect like exclusion of Na^+ from the transpiration stream and accumulation of excess Na^+ and Cl^- in vacuoles and activate ion channels, antioxidants, and compatible solutes (Munns and Tester 2008; Wang et al. 2003; Gill and Tuteja 2010; Siddiqui et al. 2012). Antioxidants and antioxidative enzymes scavenge the harmful radicals and minimize the damages induced by abiotic stresses. Antioxidants act as osmoprotectants and signaling molecules to regulate the osmotic balance of cytoplasm and trigger the expression of specific genes which play essential roles in physiology and metabolism of plants (Cui et al. 2016). Under salt stress, some plants could convert intracellular HCO_3^- into CO_2 and H_2O by carbonic anhydrase (CA) (Clausen et al. 2005; Wu and Xing 2012) and regulate photosynthesis.

Salt stress induces overproduction of reactive oxygen species (ROS) as a result of divergence of electron flow from the main transport chains of photosynthesis and respiration under salt stress. These ROS such as H_2O_2, O^{-2}, and OH^- oxidize biomolecules (lipids, proteins, nucleic acids, and carbohydrates) and disturb the plant physiological and metabolic functioning (Jaleel et al. 2009). In the plants several stress-responsive genes also play important role to provide stress tolerance toward salt toxicity. There are some mechanisms by which halophytes survive in saline conditions like dilution of excess salt by increased water content in leaves and their removal by salt glands, by bladder hairs, as well as by different plant tissues. Halophytes adopt several strategies for translocation and absorption of salt like translocation of salts by phloem and adjusting of intracellular osmotic potential by maintaining high concentrations of compatible solutes. Other mechanisms are also adopted by some plants under salt stress that is osmotic regulation for cellular homeostasis. Under salt stress, plants accumulate several osmolytes/osmoprotectants in the cytosol, such as soluble sugars, glycine-betaine, sorbitol, mannitol, trehalose, ectoine, proline, and others for osmotic adjustment or in the protection of structure (Hasegawa et al. 2000). Proline plays an essential role as an osmoregulator in plants which decreases the cytoplasmic osmotic potential, facilitates water absorption, and scavenges ROS molecules (Qureshi et al. 2013). Under hypersaline conditions many plants like canola (Xue et al. 2009), green gram (Misra and Gupta, 2005), mulberry (Surabhi et al. 2008), sunflower (Shahbaz et al. 2011), and tomato (Gharsallah et al. 2016) are reported to accumulate more proline compared to normal conditions. Salinity mainly affects two processes in plants: ionic relations and water relations. Initially plants experience water stress, which in turn reduces leaf expansion. During long-term exposure, plants experience ionic stress, which can lead to premature senescence of leaves. Response of plants to salt stress depends on the severity and duration of stress (Lakshmi et al. 1996) and on plant species (Dubey 1994).

6.3 Effect of Salinity on the Soil Microorganisms

Soil microorganisms play a key role in different soils by playing vital roles of various kinds. These are involved in nutrient cycling, in organic matter mineralization, and in maintaining plant productivity. Microorganisms have major role in oxidation, ammonification, nitrification, nitrogen fixation, and other processes related to the decomposition of soil organic matter and transformation of nutrients (Amato and Ladd 1994). Thus it is imperative to sustain high microbial activity in soils especially under different environmental stresses. Microorganisms have the ability to tolerate or adapt stresses by different mechanisms, like under salt stress conditions they synthesize osmolytes which allows them to maintain their cell turgor and metabolism. Synthesis of organic osmolytes and exclusion of sodium ions, to maintain osmotic pressure, are energy-required processes (Oren 2001). Bacterial cells have developed some strategies to survive and grow under stress conditions by accumulating osmoprotective organic compounds in their cytoplasm (Boch et al. 1996). Among different organic osmolytes, proline, and glycine-betaine among inorganic solutes, potassium cations are the commonly accumulated by salt-tolerant microorganisms (Csonka 1989). Under salt stress conditions, synthesis of alanine, aspartate, glycine, glutamic acid, serine, and threonine and upregulation of salt stress proteins are found as adaptive mechanisms in microbes (Paul and Lade 2014). Szabados and Savoure (2009) found that proline also functions as molecular chaperons with ability to protect protein integrity and enhance the activities of different enzymes. Accumulation or secretions of exopolysaccharides like xanthan (Sharan et al. 2008) and mauran (Llamas et al. 2012) are also reported under salt stress conditions.

Many studies showed that salinity negatively affects microbial activities, microbial biomasses, and alterations in microbial community structure (Elmajdoub et al. 2014; Batra and Manna 1997; Setia et al. 2011). Salinity reduces microbial biomass mainly because the osmotic stress results in drying and lysis of cells. Under salinity not only low microbial biomass is observed, but it is often found with a decreasing ratio of fungal to bacterial biomass (Pankhurst et al. 2001). In salt-affected soils, organic matter (OM) content is also found to be low, and it may also negatively affect soil microbial biomass (Sardinha et al. 2003). In laboratory studies it has been found that additions of salt influence and reduce microbial activity (Setia and Marschner 2013) and also soil respiration (Garcia and Hernandez 1996). Some studies showed that soil respiration decreased with increase of EC (Wong et al. 2009). This suggests an adverse impact of salinity on microbial activity and the decomposition of organic matter on the existing microbial community, which is not yet adapted to higher levels of salinity. Pathak and Rao (1998) found that although addition of organic matter can stimulate enzyme activities and microbial biomass, still these are negatively correlated with concentration of salt.

Soil enzyme activities like alkaline phosphatase, β-glucosidase, catalase, dehydrogenase, and urease are affected by salinity (Garcia and Hernandez 1996; Singh 2016; Zheng et al. 2017) and are generally found lower in naturally saline soils than in non-saline soils (Ghollarata and Raiesi 2007). With increasing salinity enzyme activity decreases, indicating that there is a direct negative effect of salinity on enzyme activity (Saviozzi et al. 2011). High salt concentrations denature proteins and also reduce their solubility, and it may result in lower enzyme activity. Some ions also interfere protein synthesis in the cells by preventing the binding of ribosomes to mRNA (Elsheikh and Wood 1989). High salt concentration can disperse colloids, making extracellular enzymes more prone to decomposition

(Garcia and Hernandez 1996). In the cytoplasm of microbial cells at high concentrations of salts, salting-out process takes place which can lead to enzyme inhibition. Some ions also cause toxicities due to the interactions of the ions with inhibitory binding sites of enzymes (Serrano 1996).

Abundance of fungi and bacteria are also influenced by presence of salts in soils. Fungal-to-bacteria ratio is reported to be lower in salt-affected soils (Chowdhury et al. 2011a, b). It may be because fungi are more sensitive to high salt concentrations than bacteria. The cell membrane lipids are also sensitive toward salinity. They found to transform with increasing levels of salinity either by modifying the types of existing fatty acids or by changing the preexisting phospholipids (Zhang and Rock 2008). But some researchers reported opposite to this as they found that fungi are more tolerant to salt exposure than bacteria; it may be because of ability of fungi to cope with high osmotic pressure by high concentration of organic substrates in the cell (Reischke et al. 2014) or may be because of chitinous cell walls which offer better protection against changes in moisture (Strickland and Rousk 2010). Moreover, the different localization of the proton gradient used for energy generation in cells could make fungi more resistant to changes in the cation concentration outside the cell. Soil salinization can favor fungi over bacteria, which result in a shift toward a more fungal-dominated community composition. Increase in the abundance of fungal biomarkers was also observed in response to both increasing concentration of salts and drying of soil (Kakumanu and Williams 2014). Salts associated with soil salinization do not impose the same effect on the microbial community. Salts like SO_4^{2-} and Cl^- salts as well as K^+ and Na^+ salts have different toxicity and they affect microbes differently (Tavakkoli et al. 2010). Microbes react to drought in a similar way as to high salt concentrations, by accumulating osmolytes inside the cell (Schimel et al. 2007). Saline soils are assumed to harbor communities that use C sources less efficiently than communities in non-saline soils (Yuan et al. 2007).

6.4 Role of Microbes in Mitigating Salinity Effect

Research on the development of salt-tolerant transgenic plants (Zhang et al. 2001) has gained momentum during last two decades, but this approach cannot be fully applied in agriculture due to current rules, regulations, and uncertainty of public acceptance on the use of plants with genetic modifications. These approaches are also time-consuming and labor-intensive (Coleman-Derr and Tringe 2014). Alternative microbial strategies to alleviate damage caused by salt have attracted considerable attention. Plant growth-promoting microorganisms found in association with plants grown under stress like high salinity may have been adapted to these conditions and could significantly contribute in the maintaining plant health (Table 6.1). These microbes, in order to persist in the adverse conditions, expanded their biochemical activities in the rhizosphere that influence the survival and growth of plants (Sadeghi et al. 2012). Plant growth-promoting microorganisms are found more in the rhizosphere of plants because plants construct favorable conditions by the secretion of

Table 6.1 Effect of plant growth promotor rhizobacteria (PGPR) on growth of different crops

Microorganism	Plant	Mechanism	References
Pseudomonas fluorescens	Maize	Indoleacetic acid (IAA) production	Zerrouk et al. (2016)
Rhodopseudomonas palustris	Cucumber	Plant growth-promoting traits such as the production of IAA and ALA, nitrogen-fixing, potassium and phosphorus-solubilizing ability	Ge and Zhang (2018)
Alcaligenes sp., *Bacillus* sp., and *Ochrobactrum* sp.	Paddy	1-aminocyclopropane-1-carboxylate (ACC) deaminase	Bal et al. (2013)
Raoultella planticola	Cotton	ACC deaminase	Wu et al. (2012)
Trichoderma asperellum	Cucumber	Phosphate solubilization, ACC deaminase activity, auxin and siderophore production	Qi and Zhao (2013)
Bacillus fortis 1, *Pseudomonas aeruginosa*	Capsicum	IAA synthesis, ACCD activity, P solubilization, and siderophore production	Yasin et al. (2018a)
Pseudomonas fluorescens	Black gram	IAA synthesis, ACC activity, P solubilization, and siderophore production	Yasin et al. (2018b)
Pseudomonas fluorescens and *pseudomonas putida*	Canola	ACC deaminase	Jalili et al. (2009)
Pseudomonas aurantiaca, *Pseudomonas extremorientalis*	Wheat	IAA production	Egamberdieva (2009)
Pseudomonas fluorescens and *Azospirillum brasilense*	Wheat	Auxin production and phosphate solubilization	Kadmiri et al. (2018)
Bacillus subtilis and *Pseudomonas* sp.	Tomato	Phosphate solubilization, ACC deaminase activity, IAA production, siderophore production	Kumar et al. (2018)
Variovorax paradoxus	Pea	ACC deaminase	Wang et al. (2016)
Enterobacter sp.	Sugarcane	ACC deaminase	Kruasuwan and Thamchaipenet (2018)
Enterobacter aerogenes and *Pseudomonas aeruginosa*	Alfalfa	ACC deaminase	Liu et al. (2018)
Pseudomonas fluorescens	Wheat	ACC deaminase	Safari et al. (2018)
Enterobacter sp.	Wheat	ACC deaminase	Sarkar et al. (2018)

(continued)

Table 6.1 (continued)

Microorganism	Plant	Mechanism	References
Bacillus amyloliquefaciens	Soybean	Gibberellic acid, abscisic acid production, and phosphate solubilization	Kim et al. (2017)
Achromobacter piechaudii	Tomato	ACC deaminase	Mayak et al. (2004)
Azotobacter sp.	Maize	IAA, phosphate solubilization, and nitrogen fixation	Rojas-Tapias et al. (2012)
Curtobacterium flaccumfaciens and *Ensifer garamanticus*	Barley	IAA, phosphate solubilization, nitrogen fixation, and phytate mobilization	Cardinale et al. (2015)
Curtobacterium albidum	Paddy	IAA, ACC deaminase, exopolysaccharide (EPS), HCN, siderophore, phosphate solubilization, and nitrogen fixation	Vimal et al. (2018)
Ochrobactrum intermedium	Peanut	IAA, ACC deaminase, organic acids, and siderophore	Paulucci et al. (2015)
Klebsiella sp.	Oat	Phosphate, potassium and zinc solubilization, IAA production, ACC deaminase, siderophore production and NH_3 production	Sapre et al. (2018)
Enterobacter cloacae	Canola	PGPR activities	Li et al. (2017)
Pseudomonas spp.	Wheat	ACC deaminase	Nadeem et al. (2013)
Enterobacter sp.	Okra	ACC deaminase	Habib et al. (2016)
Pseudomonas and *Bacillus*	Soybean	Proline accumulation and lipoxygenase activity	Kumari et al. (2015)
Pantoea dispersa	Chickpea	P solubilization, siderophores, IAA production, and ACC deaminase production	Panwar et al. (2016)
Pseudomonas spp.	Tomato	ACC deaminase	Win et al. (2018)
Hartmannibacter diazotrophicus	Barley	ACC deaminase	Suarez et al. (2015)
Xanthomonadales sp.	Fodder beet	Siderophores, IAA, and cellulolytic activity	Piernik et al. (2017)

root exudates, sugars, amino acids, organic acids, and signaling molecules in rhizospheric zone (Singh 2015), and in turn, the microbes provide a number of plant growth-promoting benefits to plants. By the multiple mechanisms (Fig. 6.1), such as production of IAA, ACC deaminase, exo-polysaccaride, siderophore, phosphate solubilization, and nitrogen fixation, antifungal activity, these PGPMs play important role in plant growth promotion (Nehra and Choudhary 2015; Choudhary et al. 2018). PGPMs also contribute to sustaining the intrinsic resistance of plant to pathogens, thus protecting them from diseases (Dodd and Pérez-Alfocea 2012;

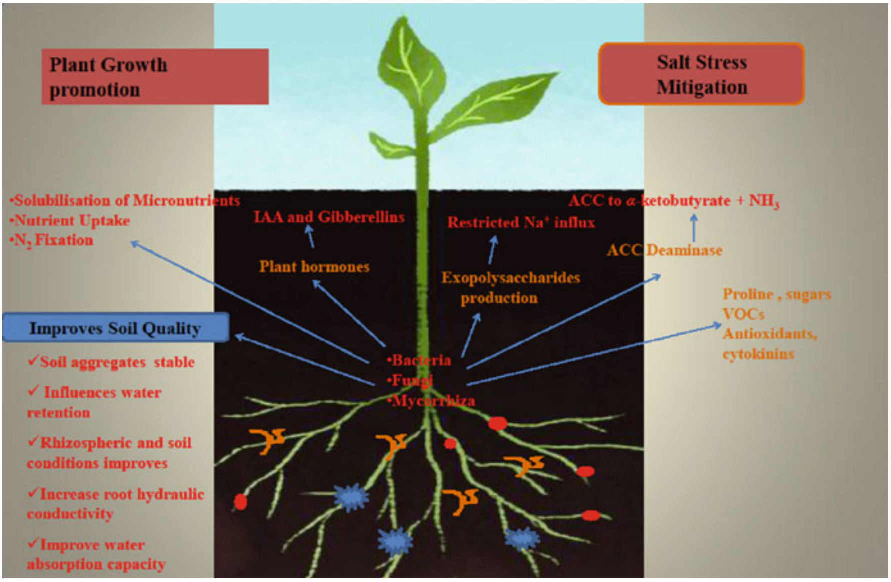

Fig. 6.1 Different PGPR activities influence plant growth

Dobbelaere et al. 2003). Plant growth-promoting bacteria isolated from salt-affected soils also help in mineralization of N and solubilization of P, thereby enhancing the growth and yield of crop plants (Arora and Singh 2017). In some bacteria the pigments were found having different antioxidant properties which make these salt-tolerant microbes helpful in the growth of plants (Banik et al. 2018).

6.4.1 Exopolysaccharides

Bacterial polysaccharides are the sugar complex that are synthesized inside their cell and secreted into the environment, or these are synthesized extracellularly by the enzymes attached to the cell wall. These polysaccharides are known as extracellular polymeric substances (EPSs) or exopolysaccharides (Nwodo et al. 2012). Exopolysaccharides have water-holding and cementing properties; they play an important role in the formation and stabilization of soil aggregates as well as in the regulation of nutrient and water flow across the plant roots (Tisdall 1994). Ashraf et al. (2006) found EPS-producing bacteria increase root growth of wheat plants and described that increased roots can tolerate the adverse effects of salt stress through enhanced soil water uptake. They also restrict the Na^+ influx in plants and also accelerates the soil microbial process which are involved in cycling and availability of the soil nutrients to the plants. EPS-producing bacteria provided a "blanket salt-tolerant cover" to the roots by enhancing the degree of soil aggregation which are formed near roots (Ashraf et al. 2006) and also enhance size of soil macropores which results in the increased absorption of water and fertilizer (Upadhyay et al. 2011). Mohammed (2018) reported that the activities of biofilm formation and exopolysaccharide production of strain *Pseudomonas anguilliseptica* SAW 24 at different salt concentrations enhanced plant height and fresh and dry weight of faba bean plants. Upadhyay et al. (2011) found the inverse correlation between the population density of bacteria that are producing EPS in the rhizosphere and the Na^+ concentration. As Na^+ decreases with the increase of the population, it becomes unavailable for plant uptake, which alleviates the salt stress in plants. Vimal et al. (2018) isolated a strain of *Curtobacterium albidum* from the saline soil and inoculated it on paddy plant. This inoculation resulted in declined acquisition of Na^+ in paddy plants. It could be because of exopolysaccharide production by isolate. These exopolysaccharides have the potential to bind cations (especially Na^+) which are present in the root zone, which prevents their movement from roots to leaves, thus protecting plants from salinity stress (Ashraf et al. 2004). In these plants an elevated level of K^+ accumulation was also observed, it may be because of prevention of cellular K^+ efflux to maintain cytosolic K^+/Na^+ (Assaha et al. 2017). Inoculation of efficient PGPM enhances the plants' ability to maintain K^+/Na^+ ratio, which is an important adaption toward salinity stress (Nadeem et al. 2013).

6.4.2 Anti-oxidative Enzymes

Under salt stress photosynthetic pigment contents (chlorophylls and carotenoids) decrease due to high concentration of Na^+ which creates osmotic stress in plant cells (Vimal et al. 2018). Due to stress conditions, production of reactive oxygen species (ROS) occurs which causes injury to proteins, lipids, and nucleic acids (oxidative stress situations) (Miller et al. 2008). Many studies show that PGPM inoculation significantly increases photosynthetic pigments in plants (Upadhyay and Singh 2015; Kumar et al. 2017; Vimal et al. 2018). Plants have their own defense enzymatic systems that reduce the damages caused by stress-induced oxidative stress. In the plants, antioxidative enzyme production enhances to neutralize the adverse impact of higher salinity stress (Gill and Tuteja 2010). These antioxidant enzymes also protect the cells and maintain their hydrated state. These functions of antioxidant enzymes provide resistance against salt, drought stress, and cellular dehydration. These include proline, glutamate, glycine-betaine, carnitine, mannitol, sorbitol, and sucrose (Hasegawa et al. 2000). The proline content produced by plants in response to salt stress has also been reported as a potent antioxidant. Proline has the capability to manage oxidative adjustments and protects proteins, lipids, and nucleic acids under salt stress conditions (Upadhyay and Singh 2015). The proBA genes derived from *Bacillus subtilis* reported to enhance proline synthesis in transgenic *Arabidopsis thaliana* with conferred salt tolerance to the plants (Chen et al. 2007).

6.4.3 Indole-3-Acetic Acid Production

Indole-3-acetic acid (IAA) is a phytohormone of auxin class that involve in root initiation, cell enlargement, and cell division. IAA-producing microorganisms could help to increase the root growth and root length of plants in a way these microbes can contribute to maintain the leaf growth and plant growth under the conditions of salinity (Munns 2002; Boiero et al. 2007). Egamberdieva (2009) reported that growth regulators considerably alleviated salinity-induced dormancy of wheat seeds. IAA-producing bacteria also can induce resistance to root rot with significantly increase in shoot and root growth and dry matter of cotton plant in saline soils. IAA-producing microbes can also increase the concentration of N, P, Fe, and Mn in wheat shoots under both normal and saline conditions (Sadeghi et al. 2012). IAA-producing bacteria *Kocuria turfanensis* strain 2 M4 isolated from the rhizospheric soil of halotolerant plant *Suaeda fruticosa* reported to increase length of the groundnut plant and fresh biomass (Goswami et al. 2014). After dual inoculation with *Pseudomonas* sp. and *Bacillus cereus*, the levels of IAA and ABA were found increased in leaves of wheat growing in saline soil (Ul-Hassan and Bano 2014). Purple phototrophic bacterium *Rhodopseudomonas palustris* G5 was found to enhance the growth as well as induced systemic resistance in the seedlings of cucumber under salt stress by the production of growth hormones, antioxidant enzymes and soluble sugars, as well as nutrient (N, P, K) balance (Ge and Zhang 2018). Jha and Subramanian (2013) reported osmotolerant bacteria that have the potential to enhance the germination of rice seeds under saline conditions. This is probably due to the attribute of the inoculated bacteria for IAA production which plays an important role in the germination of seeds. Many studies have shown that under conditions of environmental stress, microbial inoculants not only promote plant growth but also benefit plant health (Arora et al. 2017).

6.4.4 ACC Deaminase Production

Ethylene is the hormone released by the plants under the physiological response; when they are exposed to different types of stresses, they can also be known as a stress hormone. Ethylene is an effective plant growth regulator which efficiently works at low concentrations. Ethylene at large quantities (~100 μL/L) are synthesized during senescence and fruit ripening (Glick 2005). Under salt stress, the biosynthesis of ethylene can increase due to the utilization of 1-aminocyclopropane-1-carboxylic acid (ACC) as an immediate precursor, which may lead to physiological changes in plants. Salt stress stimulates the condition of plant maturation by producing high level of ethylene. Controlled ethylene production in plants that is accelerated due to salt stress can improve growth of plants under stress conditions. Microbes that can synthesize the ACC deaminase enzyme have the potential to hydrolyze ACC into α-ketobutyrate and ammonia, which can decrease the ethylene stress in plants (Glick et al. 1998).

Mayak et al. (2004) reported that tomato seedlings inoculated with *Achromobacter piechaudii* containing ACC deaminase significantly ameliorate the salt stress. Similarly, Ali et al. (2014) observed greater numbers of flowers and buds in *Pseudomonas fluorescens*-treated tomato plants than control plants. ACC deaminase-containing PGPR can reduce the deleterious effects of environmental stress and can enhance stress tolerance of plants by a variety of mechanisms such as the synthesis of phytohormones, mineral solubilization, nutrient uptake, increased leaf area, increased chlorophyll and soluble protein content, and antioxidant enzyme activities (Dobbelaere et al. 2003). Ali et al. (2014) confirmed the effect of ACC deaminase on plant growth under salinity stress by giving pretreatment to tomato plants with wild-type ACC deaminase-containing strains of *Pseudomonas fluorescens* and *Pseudomonas migulae*. It was found that these plants were healthier and grew to a much larger size compared to plants pretreated with the ACC deaminase-deficient mutants or no bacterial treatment. Similarly, Saravanakumar and Samiyappan (2007) reported that the ACC deaminase-containing *P. fluorescens* TDK1 increased the vigor index of groundnut seedlings significantly under salt stress condition as compared to plants pretreated with a strain lacking ACC deaminase activity. Gamalero et al. (2010) observed significantly higher root and shoot fresh biomass of cucumber plants inoculated with wild-type *P. putida* UW4 and *Gigaspora rosea* BEG9 than the plants that received ACC deaminase-deficient bacteria and untreated control plant salt stress. ACC deaminase-containing PGPR isolate *Enterobacter* sp. UPMR18 can help in consequently improving the growth of okra plants under salt stress (Habib et al. 2016). Similarly ACC deaminase-containing salt tolerant bacteria were reported to increase biomass in different crops (Siddikee et al. 2010, 2011). In a study carried out on maize plants inoculated with ACC deaminase producing PGPR culture, the high K^+/Na^+ ratios has been demonstrated which was due to increased plant N, P, and K uptake (Nadeem et al. 2009, 2013). Similar results were found in tomatoes which showed increased P, K^+, and Ca^{2+} uptake under salt stress conditions (Mayak et al. 2004). Heydarian et al. (2018) found that transgenic lines of *Camelina sativa* expressing *acdS* exhibit increased salinity tolerance and also affected the expression of genes involved in modulating the level of reactive oxygen species (ROS) to prevent cellular damage.

The PGPR can also alleviate osmotic stress by maintaining higher stomatal conductance and photosynthetic activities. By this function PGPRs can inhibit the accumulation of toxic ions such as Na^+ and Cl^- and improve leaf K^+/Na^+ ratio (Pérez-Alfocea et al. 1993).

6.5 Role of Mycorrhiza in Mitigation to Salt Stress

Mycorrhiza is the symbiotic relationship of plant roots and fungi which is beneficial to each other. There are two types of mycorrhiza arbuscular mycorrhizae (AM) and ectomycorrhizae (ECM); they are differentiated on the basis of their associations with plants. AM are the type of fungi which are most abundantly found in agricultural fields. These mycorrhiza also form symbiotic association with trees as well as with also aquatic plants. These mycorrhizal fungi penetrate into the cortical cells roots and form a peculiar haustoria-like structure called arbuscules. These arbuscules are responsible for the exchange of nutrition and metabolites between fungus and host plants. The AM fungal hyphae also expand into the soil, and the function of the hyphae is to assist the plants to absorb mineral nutrients and water from the soil. These fungal hyphae present in soils also improve the soil porosity and structure. Mycorrhizal association demonstrate several growth promotion properties by several mechanisms. These mechanisms include production of several plant growth-promoting metabolites like phytohormones, amino acids, and vitamins. Mycorrhiza also has the nutrient-solubilizing and nutrient-mineralizing potential (Evelin et al. 2009; Bothe 2012). It has been reported by several researchers that mycorrhizal fungi can enhance plant tolerance against various stresses like drought, salinity, and heavy metals and also provides protection from pathogens (Beauchamp et al. 2009). Hence they can help in improving crop growth and yield. Along with supplying nutritional as well as structural advantages to plants, they also provide other benefits like production and accumulation of secondary metabolites around the roots, help in osmotic adjustment in osmotic stress, facilitate nitrogen fixation, and enhance photosynthesis. They also confer resistance to plants against biotic and abiotic stresses (Hashem et al. 2015). It has been reported that *Glomus* spp. is the VA mycorrhizal fungi that are most commonly found in the saline soil (Juniper and Abbott 1993). This suggests that this may be adapted to grow under saline conditions. It has also been reported that VA mycorrhiza species distribution remarkably varies with increase in salinity (Stahl and Williams 1986). It has been observed by Aliasgharzadeh et al. (2001) that *Glomus intraradices*, *G. versiform*, and *G. etunicatum* are the most predominant species of arbuscular mycorrhizal fungi (AMF) in the salt-affected soils of the Tabriz plains. Somehow, few studies also indicated that the mycorrhizal fungi can increase growth of plants in salt-affected soils which proves that VA mycorrhizal fungi has the competency to protect plants from salt stress (Yadav et al. 2017).

It has been documented in several studies that mycorrhiza enhance nutrient uptake in salt stress also (Chang et al. 2018). AMF enhances the uptake of nutrients and hence influences the concentration of mineral the nutrients (especially phosphorus which is a complex nutrients) of plants under salt-stressed conditions. These functions occur mainly because of the supply of nutrients to the root system and increased transportation of minerals (absorption and/or translocation) by AMF (Zhu et al. 2015). Phosphorus gets precipitated in with excessive amount of Ca^{2+}, Mg^{2+}, and Zn^{2+} ions present in saline and sodic soils due to which it gets soils become unavailable to plants because phosphate ions precipitate due to which absorption reduces. Mycorrhizal inoculation to plants increases the phosphorus concentrations in plants as the extensive hyphae of the fungus which allows them to explore more soil volume than the non-mycorrhizal plants which leads them to enhanced P uptake (Fileccia et al. 2017). Facilitating phosphorus solubilization in salt-stressed and water-deficit conditions is the key mechanism for mitigating stress in crops. Mycorrhizae also help in increasing nitrogen availability to the host crops under salt-stressed conditions. Salt present in soil interferes nitrogen assimilation to plants as well as nitrate uptake which leads to reduction in protein synthesis. It has been reported that AMF facilitate better assimilation of nitrogen to the host plants. The mycelium that grows in soil take up inorganic nitrogen from the soil in the form of nitrate and assimilate it to arbuscule-containing cells via nitrate reductase, and the GS-GOGAT cycle of the plants convert it into arginine. Other mechanisms demonstrated by AM to mitigate salt stress on crop growth are variation in Na^+ and K^+ uptake. Under salt-stressed conditions, the mycorrhizal fungi also maintains a high K^+/Na^+ ratio in the associated plants. Mycorrhizal colonization of host plants has been shown to prevent Na^+ translocation to shoot tissues, while enhancing K^+ absorption under saline conditions (Wu et al. 2005). Due to the maintenance of the high K^+/Na^+ ratio by mycorrhizal fungi, the plants gets protected from the disruption of enzymatic processes and inhibition of protein synthesis in the cells. However, AM fungi have also been reported to sometimes increase the Na^+ uptake. Hammer et al. (2011) reported that AM fungi can selectively take up elements which act as osmotic equivalents such as K^+ and Ca^{2+}, while they does not absorb toxic excessive Na^+. High concentration of Na^+ present in the salt-affected soils is very much lethal to the plants as it adversely affects the growth and in plants sensitive to salt, low K^+/Na^+ ratio has been observed under salt stress. Hence, high K^+/Na^+ ratio in plants is found to be the potential indicator of salt-tolerant plants.

Proline is known to act as an osmoregulator under stress conditions in plants. It has been known that under stress conditions, plants accumulate proline as a protective and nontoxic osmolyte which maintains osmotic balance in cells under low water potentials (Auge et al. 2014; Wu et al. 2010). Proline functions as a repository for energy as well as source of nitrogen to survive during salt stress conditions. Some studies have also exhibited that mycorrhizal symbiotic association in plants affects the physiological processes of plants hence helps accumulating more proline contents. Plant which is colonized by AMF gets more accumulation of proline and also been protected in salt stress conditions (Auge et al. 2014).

There are several many other mechanisms by which AM fungi facilitate the plant growth under salinity stress. These mechanisms are the regulation of plant nutrition, modification in physiological and enzymatic activities, and alteration of the root architecture to facilitate water uptake. There are several physiological processes that are influenced by plant mycorrhizal symbiosis; these involve mainly osmoregulation in which they enhance carbon dioxide exchange rate, water use efficiency, and stomatal conductance (Aroca et al. 2007). It has been reported that mycorrhiza creates modification in root architecture as they promote better root growth by numerous branching of roots, and due to better root formation, mycorrhizal symbiotic plants absorb water more efficiently under water-deficit environment (Mo et al. 2016).

Mycorrhizal fungi are being found to modulate the stomatal conductance. The hypothesis behind this phenomenon is that abscisic acid is known to regulate the stomatal conductance by closing stomata under stress conditions; it has also been reported several times that mycorrhizal fungi influence the abscisic acid concentrations in plants under stress (Auge et al. 2015). In a study carried out by Aroca et al. (2013), it has been reported that high abscisic acid content was found in lettuce plants treated with mycorrhizal fungi. Mycorrhizal fungi can also mitigate salt stress in plants by absorbing water from their hyphae and facilitating water transport to plants, thus improving water status of the mycorrhizal symbiotic plants (Subramanian et al. 1995).

Mycorrhizae also can enhance soluble sugars and electrolyte concentrations in host plants. It has been reported by Ortiz et al. (2015) that improved osmoregulation capacity that was found in AM-inoculated maize was due to higher soluble sugar and electrolyte concentrations in the cells. Al-Garni (2006) reported that increased sugar concentrations were found in the plants of *Glycine max* and *Phragmites australis* inoculated with mycorrhizal cultures. This high sugar level in mycorrhizal plants may be due to hydrolysis of starch to sugars by mycorrhizal fungi. A study carried out by Zhu et al. (2016) on wheat to check the effect of arbuscular mycorrhiza in wheat (*Triticum aestivum* L.) under salinity stress showed that salinity stress decreases the AM colonization; however AM inoculation increases the plant dry weight under salinity stress. Effect of AM inoculation also increases stomatal conductance, density, size, and aperture in plants. AM fungi also enhanced nutrient use efficiency by altering plant C assimilation and N uptake. AM plants had higher soluble sugar concentration and K^+/Na^+ ratio compared with non-AM plants. It can be concluded that AM symbiosis improves plant growth at vegetative stages through increasing stomatal conductance, enhancing NUE, accumulating soluble sugar, and improving ion homeostasis in plants grown at salinity stress.

6.6 Halophilic Microbes

The halophilic microbes are extremophiles that prosper in environments with very high salt concentrations as these are the salt-loving microorganisms that are well-known by their distinctive requirement of high salt for their growth and have developed physiologically and genetically to endure in hypersaline environments. Halophiles include prokaryotic and eukaryotic salt-loving microorganisms of which are capable of balancing high osmotic pressure (Yoshida et al. 1991). These organisms have developed a number of biochemical approaches to maintain cell structure and function under high salinity (Cayol et al. 1994; Xin et al. 2000; Yoon et al. 2002). The diversity among halophiles depends on the salt concentration, temperatures, pH conditions, and redox conditions that the microbes are faced (Arora and Vanza 2018). Halophiles play an important role in the carbon and phosphorus transformations under in saline environments (Donachie et al. 2005).

With regard to the salt concentration, halophiles are able to produce hydrolytic enzymes in hypersaline environment that possess a potential importance in many of the industrial sectors (Tang et al. 2010). Moderately halophilic bacteria represent a group of microbes that are widespread in saline areas. These organisms show optimum growth at 5–15% NaCl (Yang et al. 2011; Ray et al. 2013; Arora et al. 2019). The extremely halophilic microbes can grow at salt concentrations above 20% (w/v) to saturation named (Yoshida et al. 1991),while slightly halophilic microorganisms can grow optimally in media containing 2–5% of NaCl concentration (Saker et al. 2015).

Halophilic or halotolerant microbes are isolated from diverse hypersaline environments, viz., solar salterns, hypersaline lakes, the Dead Sea, and underground salt deposits. The halotolerant plant microbiomes (epiphytic, endophytic, and rhizospheric) have been characterized for tolerance to salinity as well as other associated beneficial attributes. *Actinobacteria*, *Bacteroidetes*, *Euryarchaeota*, *Firmicutes*, *Proteobacteria*, and *Spirochaetes* are major phyla consisting salt-tolerant microbes. Some halophilic microbes not only can survive under high salt concentration but also possess plant growth-promoting traits such as *Ammoniphilus*, *Arthrobacter*, *Azospirillum*, *Bacillus*, *Brevibacillus*, *Brevibacterium*, *Haloarcula*, *Halobacillus*, *Halococcus*, *Haloferax*, *Halolamina*, *Halomonas*, *Halorubrum*, *Haloterrigena*, *Lysinibacillus*, *Marinobacter*, *Marinospirillum*, *Oceanobacillus*, *Paenibacillus*, *Penicillium*, *Pontibacillus*, *Pseudomonas*, *Sediminibacillus*, *Sporosarcina*, *Streptomyces*, *Thalassobacillus*, and *Thermonema*. The halophilic microbes help in plant growth under harsh saline environments as they have ability to produce phytohormones, i.e., IAA, gibberellic acids, and cytokinin, and solubilize and bind nutrients like phosphorus, potassium, and zinc. These also possess plant defense reactions against pathogens. Hence the halophilic PGP microbes can increase the plant growth, yields, and nutrient uptake under the saline condition. The biodiversity of halophilic microbes has been reported from diverse ecosystems with their functional PGP attributes and mechanisms of action for amelioration of salt stress (Arora et al. 2014b).

6.6.1 Halophilic Endophytic Bacteria

Endophytes are the microbes that reside inside the plants. These endophytes are more protected from adverse environmental changes than the bacteria present in the rhizosphere and phyllosphere as they have close interaction with host plant and also face less competition for nutrients (Weyens et al. 2009). They can help in degradation of the toxic elements taken by the plants, thus lowering the phytotoxicity, and useful for phytoremediation of environment. Evidences indicate that endophytes are able to contribute to phytoremediation of organic pollutants and heavy metals (Thijs et al. 2014; Becerra-Castro et al. 2013). Endophytic bacteria having PGP attributes can directly enhance plant growth by production of auxins and cytokinins, or they may help in increasing the availability of nutrients through numerous biochemical processes, viz., N_2-fixation, phosphate solubilization, and siderophore production, and thereby increasing iron availability. Indirectly, these bacteria can limit stress ethylene production by the secretion of ACC deaminase, through chemical induction of plant defense mechanisms, or by degradation of contaminants (Thijs et al. 2014; Weyens et al. 2009). Therefore, the endophytic microorganisms are suitable for phytoremediating salt and drought stresses. From the west coast of India, halophilic endophytic bacteria were isolated from leaves of dominant halophyte or salt-tolerant plant species, and these

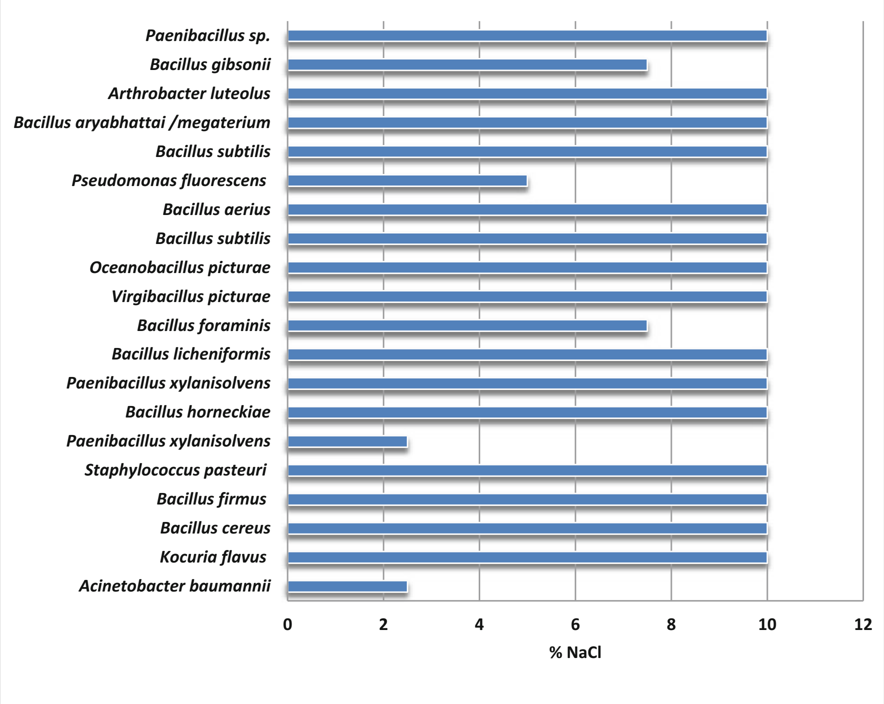

Fig. 6.2 NaCl tolerance of endophytic bacteria isolated from halophyte leaves

endophytes were assessed for their plant growth promotion traits (Arora et al. 2014a; Arora and Vanza 2017). Twenty isolates were screened based on salt tolerance and their fast growth, and all of them showed good growth at 2.5% NaCl concentration, while 18 isolates grow up to 5% NaCl, 17 isolates showed growth at 7.5% NaCl, and 15 could tolerate up to 10% NaCl concentration (Fig. 6.2, Arora et al. 2014a). Two isolates, viz., *Bacillus foraminis* and *Bacillus gibsonii*, could tolerate up to 7.5% NaCl, while *Pseudomonas fluorescens* up to 5% NaCl concentration and *Acinetobacter baumannii*, and *Paenibacillus xylanisolvens* tolerated only up to 2.5% NaCl (Fig. 6.2). Remaining other isolates was able to tolerate NaCl concentration of 10% NaCl in the media. Overall, the growth rate of endophytes decreased with increasing concentration of NaCl in the media. The population of bacterial isolates was found to be maximum from the leaves of *Sphaeranthus indicus* (40%) and was minimum in leaves of *Salicornia brachiata* (10%). Out of the 20 screened halophilic endophytic bacteria, 3 were pigmented and 17 were non-pigmented. Seven isolates were Gram-negative cocci while two Gram-positive cocci, four Gram-negative bacilli, and seven Gram-positive bacilli. Of the isolates, 18 were motile, whereas only two were nonmotile. Eleven isolates showed positive results for oxidase, while all endophytes showed negative catalase test. The enzymatic activity of endophytic isolates revealed that

50% isolates exhibited amylase activity, and only 15% isolates showed positive for urease activity (Arora et al. 2014a).

Of the 20 endophytic bacterial isolates screened for PGP characters, 6 (30%) and 2 (10%) isolates were positive for ammonia production and phosphate solubilization. Only 4 (20%) were mixed acid fermenters, 5 (25%) showed the production of acetoin, and none of the isolates exhibited IAA production (Arora et al. 2014a). The selected bacterial isolates were subjected to 16S rRNA gene sequencing for molecular identification, and it was observed that *Acinetobacter baumannii*, *Bacillus cereus*, *Bacillus firmus*, *Bacillus aerius*, *Pseudomonas fluorescens*, and *Bacillus subtilis* were positive for ammonia production, while phosphate solubilization was positive in *Acinetobacter baumannii* and *Pseudomonas fluorescens* isolates (Arora and Vanza 2017).

6.7 Interactions of Plant-Microbiome for Salt Stress Alleviation

Different types of stresses including salinity, drought, nutrient deficiencies, contamination, diseases and pests, etc. can alter plant-microbe interactions in the plant rhizosphere. Recent researches showed that plant sensitivity of environmental stress cues triggers the activation of signaling molecules where phytohormones play an important role (Barea 2015). The plants respond to environmental constraints through the signal input which is followed by a signal processing and finally by a signal output. As plants are exposed to multiple stresses at the same time, appropriate meta-analyses disclose a complex regulation of plant growth and immunity (Dimkpa et al. 2009). It is fundamental to understand how phytohormones interact in the signaling network and how plant-microbiome systems thrive and survive in stressed environments. This understanding is required to design biotechnological approaches to optimize plant adaptation mechanisms and also to improve the ability of soil microorganisms for stress alleviation in crop plants (Pozo et al. 2015). The mechanisms involved in plant-microbe interactions under salt stress situations are poorly understood. However, various present researches are evidencing the involvement of changes in plant morphology, physiology, transporter activity, and root exudation profiles, changes that can induce the plant to utilize microbes with stress-alleviating capacities, a strategy that is able to help crop growth and productivity under stress (Zolla et al. 2013).

Detrimental impacts of stress factors on the functionality/productivity of agricultural systems are evident, and the role of rhizosphere microorganisms in helping plants to thrive in adverse conditions is imperative (Barea et al. 2013). Plants have highly beneficial interactions with microbes, and some of these interactions involve highly sophisticated symbiosis that confers stress tolerance, viz., association with mycorrhizae and rhizobia that helps in ameliorating nutritional and water deficiencies, while others are more transitory (Etesami and Beattie 2017).

There are many challenges in deciphering the biotic and abiotic plant factors that shape the plant-associated microbiome for which the current research is trying to envisage. During Savka et al. 2013, Savka and coworkers stressed that the work on plants must focus on reprogramming transport functions, while those on microorganisms must focus on the uptake of secreted nutrients and the time-course changes in the microbial community structure. Overall, there is need for combination of all of these approaches that can improve our understanding on how to enhance the competitiveness and persistence of bacteria in the rhizosphere to finally improve plant and soil health as well as agro-ecosystem productivity.

6.8 Microbial Formulations for Enhancing Crop Production in Salt-affected Soils

Globally many researchers have worked on effect of different PGPMs on plant growth and crop yields. Limited researchers have taken their research from lab to land. To use PGPM in field requires appropriate carrier for their sustainable use. Formulation of biological agents, especially microbes with suitable carrier which remain stable during period of production, distribution, storage, and transportation, is called as bio-formulation. The formulation produced should also be easy to handle and applied by the end users and should be able to maintain or enhance activity of the organism in the field. It is also very important that these should be cost-effective so that it can easily be used by end user. The carrier should be designed such that it provides a suitable microenvironment for the PGPM and should allow an easy dispersal at the targeted site. If it is meant for seed treatment, then it should have a good adhesion, and the carrier shall guarantee the survival of the microbes on the seed as normally seeds are not immediately sown after seed coating. A good carrier for microbes should have one important characteristic: the capacity to deliver the right number of viable cells in good physiological condition at the right time (Nehra and Choudhary 2015). Although many microbes either solely or in consortia have been used to promote plant growth under salt stress conditions, here we only discussed about bio-formulations which not only contain microbial consortia but are being used with suitable carrier material. Shahzad et al. (2017) developed a multi-strain biofertilizer – Rhizogold (RG) – that helps in mitigating the impact of salinity stress on cereal crops. Three PGPR strains, viz., *Bacillus cereus* strain Y5, *Bacillus* sp. Y14, and *Bacillus subtilis* strain Y16, were used in the consortia with different carriers like compost, peat, biogas slurry, and pressmud for seed coating. It was noticed that this bio-formulation improved the exchange of gases and improved ionic, biochemical, growth, and yield attributes of wheat crop under salinity stress. The effect of bacterial fertilizers on cotton growth in moderate saline and non-saline soil conditions was evaluated by Pulatov et al. (2016) and used four bacterial fertilizers BIST, ErMalxami, Subtin, and Fitobisol, and it was observed that BIST and Subtin significantly increased the seed germination (15%), total root and shoot dry weight (13–27%), and yield (15–20%) of cotton under saline soil. Biofertilizer of heterocystous cyanobacteria, *Nostoc ellipsosporum* HH-205 and *Nostoc punctiforme* HH-206, was found to be effective in enhancing growth and yield of pearl millet – wheat crop (Nisha et al. 2018). Two strains of halophilic bacteria, viz., CSSRO2 *Planococcus maritimus* and CSSRY1 *Nesterenkonia alba*, having plant growth promotion attributes that were isolated from rhizosphere of dominant halophytes from western saline coastal region of Gujarat (Arora et al. 2012) were found to be effective in mitigating salinity stress. It was observed that inoculation of strain CSSRY1 decreased soluble Na content up to 31% at 4% of NaCl, while at 10% NaCl concentration, it reduced to only 19% sodium from the saline soil. These screened isolates were further tested in greenhouse pot experiments for plant growth promotion in wheat under salinity stress. Results showed that plant growth parameters and yield of wheat increased when wheat seeds were inoculated with halophilic bacteria and plants received saline water irrigation. Further, it was observed that there was 10–12% increase in growth, yield attributing characters, and yield of wheat at 6% level of NaCl as compared to 2% concentration of NaCl (Fig. 6.2). In saline soils, *Zea mays* seeds when inoculated with a consortia of halophilic bacteria showed increase in growth up to 10% NaCl concentration, whereas inoculation with single isolate does not promote much plant growth at this concentration of salt. The maximum fresh weight, dry weight, shoot length, and root length of maize plants were found in the case of "Consortium 5% NaCl" treated pots, 194.5% increase in fresh weight, 98.97% increase in dry weight, 15.37 cm increase in shoot length, and 7.4 cm increase in length of roots as compared to the uninoculated control plants (Arora et al. 2013). The results revealed that inoculation with these halophilic bacterial isolates can promote the growth of plants in saline soils due to production of hormone auxin and thus enhanced root growth. The other possible mechanism may be salinity stress alleviation via plant growth-promoting rhizobacteria expressing ACC deaminase activity. This enzyme enables to remove stress ethylene from the rhizosphere. Further, these halophilic/halotolerant bacteria remove sodium from the saline soil system and thus are useful in plant growth promotion in salt-affected soils. Salt-tolerant strains of *rhizobium* were also isolated from coastal saline soils and found to be useful in enhancing legume crop growth under salinity stress (Trivedi and Arora 2013). There are many other evidences which shows improvement in soil chemical, physical, and microbial properties (Cong et al. 2017; Sun et al. 2017; Nisha et al. 2018). Rhizospheric and endophytic bacteria were also found to have growth enhancement and bio-ameliorant properties. CSR-BIO containing consortia of three microbes, viz., CSR-B-2 (*Bacillus pumilus*), CSR-B-3 (*Bacillus thuringiensis*), and CSR-T-1 (*Trichoderma harzianum*), on dynamic media increased the productivity of the high-value crops like banana, hybrid vegetables, and gladiolus. This bio-formulation acts as a nutrient vitalizer, soil conditioner, and growth enhancer under salt-affected soils (Damodaran et al. 2013).

Salt-tolerant (halophilic) bacterial strains of N-fixers and phosphate solubilization bacteria (PSB) were isolated from the salt-affected soils of Indo-Gangetic plains at Regional Research Station of Central Soil Salinity Research Institute at Lucknow (Arora and Singh 2016). These strains were characterized for plant growth promotion and tested for their efficacy under different salinity levels. To enable seed application of these selected potential strains of useful soil microorganisms, these were cultured in the laboratory and prepared in suitable standardized media as liquid bio-formulations, viz., Halo-Azo and Halo-PSB (Arora and Singh 2018) (Fig. 6.3). These can be used either for seed treatment or seedling root dip or soil application with FYM/compost.

Fig. 6.3 Commercial liquid bio-formulations (Halo-PSB, Halo-Azo, Halo-Mix and Halo-Zinc) developed at ICAR- Cental Soil Salinity Research Institute

Application of these bio-formulations helps to mobilize plant nutrients like nitrogen and phosphorous through their activities in the rhizosphere soil and enhance their availability to plants in a gradual manner under salinity stress. Liquid bio-formulations "Halo-Zinc" and "Halo-Mix" having salt-tolerant strains of zinc solubilizing bacteria and consortia of PGP bacterial species, respectively, were developed and found to be effective in enhancing plant growth and yield under salt stress (Fig. 6.3). These are also helpful in maintenance of soil health, minimize environmental pollution, and cut down on the use of chemicals in agriculture. They are affordable for most of the farmers who are small and marginal. Bio-formulations are also ideal input for reducing the cost of cultivation and for promoting organic farming on salt-affected soils.

Under sodic and saline-sodic soils, the bio-formulation has been tested at farm, validated at different farmer's fields in more than six districts of salt-affected areas. The seedling dip or seed inoculation with the bio-formulation resulted in enhanced crop yields, management of soil health, and stress regulation.

These liquid bio-formulations are very beneficial for enhancing production of cereal crops mainly rice and wheat as well as vegetable crops. These can be easily used as seed treatment, seedling dip, and soil application with FYM/manure. The packing of 100 ml bottle is sufficient for treating seeds of 1 acre land or root dip. It has been found to be very effective in sodic soil, and multi-location testing of these bio-formulations was done in diverse sodic soils of Indo-Gangetic plains (Arora and Singh 2017). There was increase in rice and wheat yield by 11.5–14% under salt stress conditions in Indo-Gangetic plains (Fig. 6.4). This is the cheap and eco-friendly approach for bio-remediating salt-affected soils and optimizing crop yields in the degraded lands. Effect of integrated use of liquid bio-formulations Halo-Azo, Halo-PSB, and Halo-Zinc with 75% of recommended dose of NPK showed 6.7% increase in grain yield of salt-tolerant short duration variety of paddy grown on sodic soil of pH 9.6 over 100% recommended NPK and zinc sulfate (Singh and Mishra 2018). In coastal saline soils, the highest grain yield of 5.12 t ha^{-1} of rice variety "Sumati" was reported with combined application of liquid bio-formulations Halo-Azo and Halo-PSB compared to grain yield of 4.69 tha^{-1} in uninoculated control, indicating yield enhancement of 9.1% (Sarangi and Lama 2018).

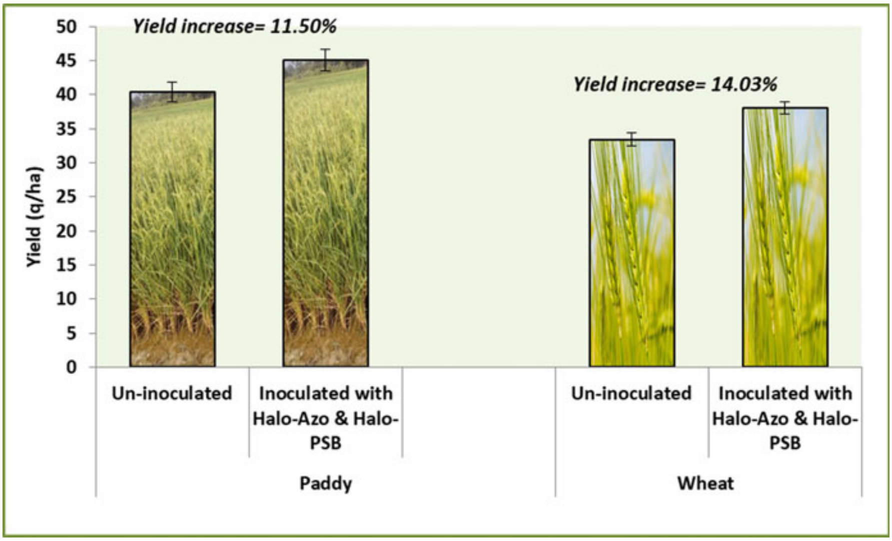

Fig. 6.4 Efficacy of liquid bio-formulations of halophilic PGP strains on paddy and wheat on sodic soils

6.9 Potential of Halophilic Microbes to Ameliorate Sodic Soil

In an attempt to bio-remediate sodic soil, inoculation of halophilic plant growth promoters in the form of bio-formulations improved soil properties apart from increasing crop growth and yields. There was substantial improvement in soil pH and exchangeable sodium content (Arora and Singh 2017). It was observed that after 2 years of continuous rice-wheat with inoculation of halophilic plant growth-promoting microbial formulations of N-fixers and P-solubilizers, soil pH reduced from initial value of 9.42 to 8.91 and 8.94. Similarly, reduction in exchangeable sodium content in soil from 416 to 238 mg/kg was noticed (Table 6.2). Exchangeable sodium percentage was reduced from 44 in control (uninoculated) to 41 (with consortia inoculation). Buildup of soil organic C (from 0.28% to 0.38%) and available N content apart from improvement in soil microbial biomass C and dehydrogenase activity was observed with application of liquid bio-formulations (Arora and Singh 2018). Soil microbial biomass C enhanced to 61 μg/g with the application of consortia over 41 μg/g where no bio-formulations were used (Fig. 6.5). Also, with organic and inorganic amendments, use of bio-inoculants of halophilic PGP bacteria ameliorate sodic soils, alleviate salt stress, and enhance rice-wheat yield (Arora et al. 2016). It was observed that the application of liquid bio-formulations has the potential to improve growth and yield of crops under salt stress and they were also found to play role in soil health improvement as observed in soil after harvest of the crop.

Table 6.2 Effect of liquid bio-formulations of halophiles on sodic soil properties after harvest

Treatment	pH (1:2)	EC (dS m^{-1})	OC (%)	Exch. Na (mg kg^{-1})	ESP
Control (FYM)	9.24	0.432	0.28	338	44
FYM+Halo-Azo	8.94	0.318	0.35	266	42
FYM+Halo-PSB	9.12	0.364	0.33	272	43
FYM+Halo-Azsp	9.18	0.385	0.31	282	43
FYM+Consortia	8.91	0.322	0.38	238	41

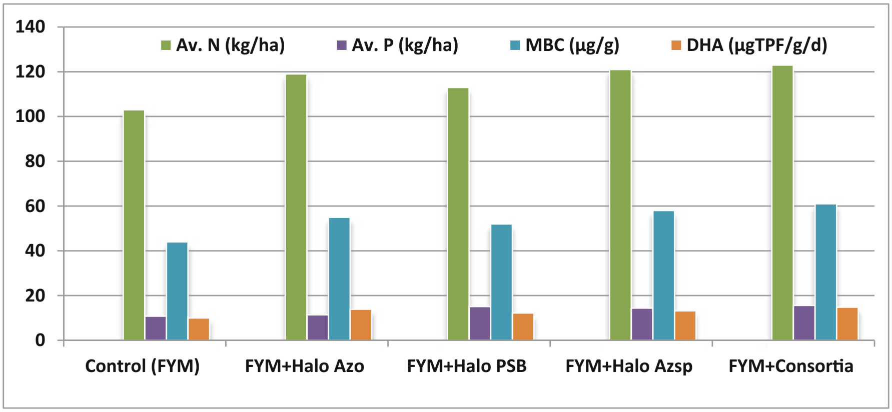

Fig. 6.5 Effect of halophilic PGP microbe inoculation on soil biochemical properties

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Salt-tolerant Microbes in Mangroves: Ecological Role and Bioprospecting Potential

7

K. Kathiresan

Abstract

Mangroves support salt-tolerant microbial communities such as microalgae, fungi, actinomycetes, bacteria as well as viruses. The microbes form the basis of the functioning of the mangrove habitats. The mangrove system is a detritus-based one that depends on the microorganisms that play a vital role in decomposing the organic matter, making the protein-rich food for fishes, recycling the nutrients and in supporting the coastal food web. In order to adapt to varied conditions of mangroves, the microbes produce novel chemical compounds of unique biological properties. However, the bioprospecting potential of the mangrove-derived microbes is yet to be properly understood for their potential applications as food, fuel, fertilizers and valuable chemicals for pharmaceutical and industrial utility.

7.1 Introduction

Mangroves are the only forest system that grow in the intertidal areas of bays, estuaries, lagoons and backwaters in tropical and subtropical regions of the world. The mangroves are one of the world's most productive forest ecosystems, and their biomass is greater than any other aquatic systems on the Earth. The mangroves are often called as 'tidal forests', 'coastal woodlands', 'blue carbon forest' or 'oceanic rain forests' (Kathiresan and Bingham 2001; Kathiresan and Qasim 2005; Kathiresan 2018). The microbial biomass is the largest component of the mangrove ecosystem, next to tree biomass (Alongi 2002), and hence the microbes in the mangrove ecosystem do play vital role in structure and function of the system.

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Mangroves are the paradise for salt-tolerant microbes by providing suitable conditions for diversified microbial communities. Studies of microbes and their interactions with mangrove ecosystem components are critical for our understanding on functioning of the ecosystem (Sahoo and Dhal 2009; Gomes et al. 2011). The microbial activities are predominant in the detritus-based mangrove ecosystem in organic decomposition, nutrient recycling, detritus food production for fishes, and in operation of coastal food web. Although the mangrove system is rich in microbial diversity, only <5% of microbial species are known so far; in many instances, neither their ecological roles nor their application potentials are known. However, recent technologies in molecular biology and genetics are promising to explore the microbial diversity (Thatoi et al. 2013). Hence, this book chapter consolidated the information about microbes in the mangrove ecosystems for their diversity, ecological role and bioprospecting potential.

7.2 Mangroves: A Microbial Paradise

Mangrove ecosystem supports varied groups of microbes for the reasons given below:

(i) The mangrove ecosystem consists of varied habitats such as forests, litter-forest floors, mudflats, faunal assemblages, associated coral reefs and seagrass ecosystems and the water bodies of rivers, bays, intertidal creeks, channels and backwaters.
(ii) The mangrove ecosystem is situated in the intertidal areas that are exposed to varied ranges of environmental conditions.
(iii) The mangrove system helps in colonization of genetically diverse groups of aquatic and terrestrial species that can tolerate varied ranges of environmental conditions.

7.2.1 Marine Microbes: Uniqueness

Ocean is microbe-based system, and the microbes do exist in all niches where life is possible. The marine microbes occupy >90% of biomass in the ocean, and their number exceeds one billion in a litre of seawater or 1 g of sea mud. The total weight of marine microbes is fantastically equivalent to that of 240 billion elephants, and the number of microbes in the ocean is remarkably 100 million times more than that of stars in the sky! The marine microbes are rich in diversity due to mutations that occur over 3.5 billion years of their existence. The marine microbes come under 100 major phyla and 18 million DNA sequences. There are 10^{29} prokaryotes and over 10 times more viruses in the world ocean (Kathiresan 2015). Even though the prokaryotes are more abundant than eukaryotic microbes, biomass in both the groups are rather similar.

The marine microbes are superior to gigantic marine mammals. For instance, *Synechococcus*, a cyanobacterial species has 2 billion years of existence on this planet, as against only 10 million years for blue whales. The cyanobacterial species has just less than one day of life, whereas blue whales have more than 10 years of life span. Regarding biomass, the cyanobacterial species has 10^5 million tons carbon as against only 10 million tons carbon for blue whales. Marine viruses store 200 million tons (2×10^{11} g^{-1}) of total carbon that is equivalent to 75 million blue whales. If all marine virus particles are placed end to end, the length will be 100 times of the distance across the galaxy (Kathiresan and Duraisamy 2006; Kathiresan 2015).

7.2.2 Marine Microbes in Indian Mangroves

The mangrove ecosystems of India have a total of 4107 biological species that consist of 925 floral and 3182 faunal species (Table 7.1; Kathiresan 2018). Such a huge biodiversity of mangrove ecosystem is not reported in any other countries in the world. Microorganisms constitute 55% of total floral species, that is, 502 microbes of 925 total floras.

Table 7.1 Numbers of biological species reported in mangrove ecosystems of India (Kathiresan 2000a, 2009, 2018)

No.	Biological group	Number of species
Floral component		
1	True mangroves	44*
2	Mangrove associate plants	86
3	Seagrass	11
4	Marine algae	557
5	Bacteria	69
6	Fungi	103
7	Actinomycetes	23
8	Lichens	32
	Total	925
Faunal component		
9	Prawns and lobsters	55
10	Crabs	145
11	Insects	661
12	Mollusks	337
13	Other invertebrates	745
14	Parasites of fish	7
15	Fin fish	554
16	Amphibians	13
17	Reptiles	84
18	Birds	513
19	Mammals	68
	Total	3182
	Grand total	**4107**

*Ragavan et al. (see next chapter of this book) reported 42 true mangrove species and 4 natutal hybrids from mangroves of India

Table 7.2 Marine microbes in different mangrove regions of India (Kathiresan 2000a, 2009)

No.	Name of species	East coast	Andaman & Nicobar Islands	West coast
1	Microalgae	199	41	152
2	Bacteria	58	13	10
3	Fungi	57	59	80
4	Actinomycetes	23	5	11
Total		337	118	253

The number of marine microbes varies with different mangrove regions of the country as shown in Table 7.2. East coast has higher number of species (337) than west coast (253 species) and Andaman and Nicobar Islands (118 species). This is coinciding with the area extent of mangrove forests along the Indian coastline: 57% in east coast, 30% in west coast and 13% in Andaman and Nicobar Islands. It reveals that the larger the mangrove forest area, the higher will be the number of microbial species. The species number so far recorded falls in a descending order: microalgae > fungi > bacteria > actinomycetes.

7.2.3 Marine Microalgae in Indian Mangroves

'Plankton' are passively swimmers. Phytoplankton or microalgae are the plant group of the plankton, and they are considered to be the 'pasture grounds' in the aquatic environment. The phytoplankton biomass is greater than the land plant biomass. If phytoplankton are absent, there will not be any life in the sea. The microalgae are the fundamental unit of marine food web by transferring energy to the higher trophic levels. The phytoplankton regulate the diversity and abundance of higher forms of life in the mangrove ecosystem. Microalgae play a vital role in primary productivity in a range from 20 to 50% of total net production in mangrove systems (Robertson and Blaber 1992). In mangrove ecosystems of India, there are a total of 307 microalgal species recorded under 4 families, namely, Chlorophyceae, Cyanophyceae, Dinophyceae and Charophyceae (Kathiresan 2000a, 2009).

Heterotrophic bacteria and microalgae (phytoplanktons) exhibit diel variation in mangrove waters, as shown in Fig. 7.1. The photosynthetic plankton are more in numbers during day time, whereas the heterotrophic bacteria exhibit a reverse trend, and they are multiplied more during night hours.

7.2.4 Marine Bacteria in Indian Mangroves

Diversified bacterial communities are present in mangrove ecosystems. The bacteria are important in sequestering nutrients, and hence the mangroves are highly productive in nutrient-limited mangrove mud (Kathiresan and Bingham 2001). The bacteria predominate in terms of biomass and productivity, next to tree biomass in the mangrove forest systems (Alongi 2002). The bacteria increase the fertility of the

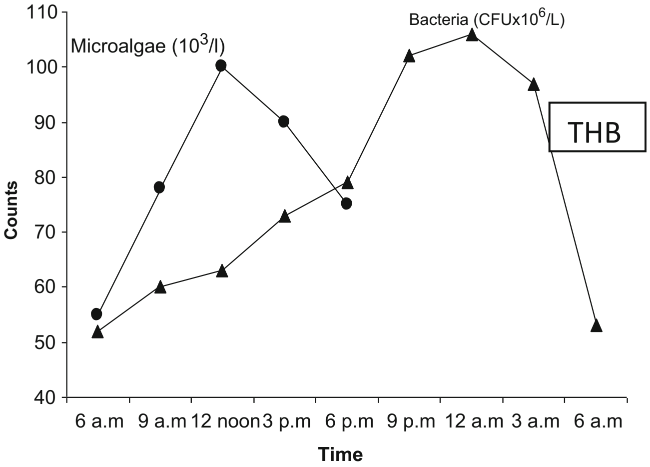

Fig. 7.1 Diel variation in counts of phytoplankton and total heterotrophic bacteria (THB) in mangrove waters in Vellar estuary, India

mangrove habitats by microbial decomposition of organic matter leading to nutrient recycling. The bacterial populations in mangroves are higher than the fungal populations. The bacteria occur as symbionts with plants and animals, as saprophytes on dead organic matter and as parasites on other organisms. The bacteria in mangrove systems have varied functions such as methanogenesis, magnetic behaviour, human pathogens, photosynthesis, nitrogen fixation and production of antibiotics and enzymes – arylsulphatase, L-glutaminase, chitinase, L-asparaginase, cellulase, protease and phosphatase (Kathiresan 2000b).

The *Cyanobacteria* (also known as blue-green algae) are an important photosynthetic component of the microbial community of mangrove ecosystems. Six species are dominant in the root-soil of mangroves, and they are *Phormidium tenue*, *P. fragile*, *Synechocystis salina*, *Spirulina subsalsa*, *Oscillatoria willei* and *O. cortiana*. Their counts range from 3.1×10^3 to 4.1×10^4 colony forming units per gram of soil, with the highest counts in summer and the lowest counts during post-monsoon in the east coast mangroves of India (Nabeel et al. 2009). The cyanobacterial diversity is higher in dense mangroves. For instance, the dense mangroves of Pichavaram have 63 species of cyanobacteria, while the sparse mangroves of Ariyankuppam have 40 species of cyanobacteria. The cyanobacterial colonies also follow a zonation pattern on the aerial roots (pneumatophores) of *Avicennia marina*. For instance, the coccoid forms are present on top of the aerial roots; the non-heterocystous and filamentous forms are in the middle part; and the heterocystous and filamentous forms colonize at the bottom of the aerial roots (Palaniselvam and Kathiresan 2002).

Nitrogen-fixing azotobacters are higher in counts in root-soil of *Avicennia* than *Rhizophora* when analysed at a monthly interval for 1 year. Besides nitrogen-fixing azotobacters, the levels of N and P are also significantly higher in *Avicennia* than in *Rhizophora* zone (Selvam and Kathiresan 2010). Perhaps this may be the reason for the luxuriant growth of *Avicennia* anywhere it occurs.

Beneficial bacteria like lactobacilli are abundant in the root-soil of mangroves. The common species are *Lactobacillus delbrueckii*, *L. palntarum*, *L. xylosus*, *L. lactis*, *L. casei* and *L. curvatus*. Their counts range between 3×10^2 and 3.1×10^4 colony forming units per gram of soil with the highest counts during post-monsoon and the lowest during summer in the east coast mangroves of India (Thiruneelakandan et al. 2009).

The mangrove habitat is predominant with anaerobic domain. There is a drastic decline in counts of heterotrophic bacteria from surface of forest floor to 30 cm depth due to drastic reduction of oxygen level in the soil profile. However, anaerobic bacteria such as methanogens, sulphur reducers, manganese reducers and iron reducers are functional in the anaerobic environment of the mangrove habitat. Among the anaerobes, the most neglected group is photosynthetic anaerobes such as purple non-sulphur bacteria and purple sulphur bacteria, and these microbes, unlike aerobic microbes, use hydrogen sulphide for donating electron instead of water. These photosynthetic anaerobic microbes may contribute significantly to the productivity of anaerobic environment of mangrove habitats, which deserve a special study.

In mangrove ecosystems of India, there are a total of 69 bacterial species recorded, under 26 genera. East coast has 58 species, and the Andaman and Nicobar Islands has 13 species, whereas the west coast is represented with only 10 species (Kathiresan 2000a, 2009).

7.2.5 Marine Fungi in Indian Mangroves

Fungi in mangrove ecosystems are active in litter decomposition and nutrient cycling and hence contributing to the fertility of the ecosystems. Fungal biomass in detritus food contributes to the food chain of detritus-feeding organisms present in mangrove ecosystems. *Aspergillus* and *Penicillium* are predominant fungal species. Marine fungi have been extensively studied and particularly the wood-inhabiting fungi since the time of Barghoorn and Linder (1944) till now. The wood-inhabiting fungi are termed as ‘lignicolous fungi’, constituting over 50% of the total 450 species of total marine fungi recorded so far. About 150 species are present only on decaying mangrove wood, aerial roots and seedlings and are categorized as ‘Manglicolous fungi’, and they mostly are coming under the class of *Ascomycetes* (Kohlmeyer and Kohlmeyer 1979).

Marine fungi colonize submerged roots, stems, and twigs as well as algae and sessile animals. The fungal species are predominantly present on mangroves such as *Rhizophora mucronata*, *R. apiculata*, *Avicennia marina*, *A. officinalis* and *Sonneratia alba.* The fungal diversity varies with the status of mangrove forests. A well-developed mangrove habitats contain a larger number of fungal species than the new mangrove habitats. Mangroves in Kerala are represented with 32 endophytic fungi, 17 pathogenic fungi and 14 wood-degrading fungi (Mohanan 2008).

Yeasts are the fungi belonging to basidiomycetes and ascomycetes. The species predominant in the root-soil are *Pichia capsulate*, *P. fermentans*, *P. salicaria*, *Saccharomyces cerevisiae*, *Candida tropicalis*, *C. albicans*, *Rhodotorula minuta*, *Cryptococcus dimennae*, *Geotrichum* sp., *Debaryomyces hansenii*, *Yarrowia lipolytica* and *Trichosporon* sp. Their counts vary between 1×10^2 and 1.4×10^4 colony forming units per gram of mangrove soil with the highest occurrence in post-monsoon and the lowest during summer (Manivannan and Kathiresan 2009).

In India, the mangrove ecosystems are represented with a total of 103 marine fungal species under 67 genera. East coast has 57 species, and Andaman and Nicobar Islands has 59 species, while the west coast has 80 species (Kathiresan 2000a, 2009).

7.2.6 Marine Actinomycetes in Indian Mangroves

Actinomycetes are microorganisms, well-known for production of antibiotics, vitamins, enzymes, pigments and nutrients. They are Gram-positive bacteria, producing cotton-like structures. Only limited work is available on biodiversity of actinomycetes in mangroves of India (Lakshmanaperumalsamy 1978; Kala and Chandrika 1993; Balagurunathan 1992; Sivakumar 2001).

In the mangrove ecosystems of India, there are 23 actinomycetes species belonging to 4 genera. Over 87% of the species are coming under the genus *Streptomyces*. East coast has all the 23 species, while the west coast has only 11 species (under 2 genera) (Kathiresan 2000a, 2009). *Streptomyces kathirae* and *Actinopolyspora indiensis* are the two species, recorded for the first time in India (Sivakumar 2001).

7.2.7 Marine Viruses in Indian Mangroves

Viruses are ubiquitous and ecologically important biological units on the planet in general and in the marine environment in particular. The viral counts estimated in the ocean are 10^{30} viruses, and if it is stretched end to end, the length may be greater than 60 galaxies (Kathiresan 2015). The viruses are active in controlling of marine environment through (i) increasing the carbon cycle, (ii) enhancing the respiratory activity, (iii) accelerating the climate change, (iv) controlling the microbial diversity, (v) exchanging the genetic materials between bacteria and (vi) disseminating the toxins by killing pathogenic bacteria and outbreak of diseases. The viruses are extremely abundant in nutrient-poor waters, while the viral attack on bacteria is higher in nutrient-rich environments, thereby controlling microbial populations in the ocean. Viral infection occurs in the ocean at the rate of 10^{23} per second, and 10–20% of marine bacteria are killed by the viruses daily with loss of 2–3% primary production (Meyer 2000; Kathiresan and Duraisamy 2006). The viruses are a predominant component of the marine food web through attacking bacteria, archaea and eukaryotic organisms. The marine viruses increase the level of respiration in the oceans, and they also reduce the level of carbon dioxide in the atmosphere by 3 gigatonnes of carbon per year. The virus can significantly affect primary production, playing a key role in population mortality, nutrient cycling, bacterial and algal biodiversity and distribution, algal blooms, dimethylsulphide release and transfer of genetic material (Kathiresan 2015).

The viruses occur abundant in mangrove systems as compared to other biotopes for controlling the populations and functions of prokaryotic and eukaryotic organisms (Badhul Haq and Kathiresan 2015).

7.3 Ecological Role of Microbes in Mangrove Systems

The microbes are key players in litter decomposition and nutrient recycling in the mangrove systems. The ‘litter-fall’ consists of leaves, stems, roots, flowers and fruits. These are colonized and decomposed by microbes, and this process releases nutrients, thereby enriching the mangrove habitat and other associated coral reefs, seaweeds and seagrass beds. The detritus is microbially decomposed organic matter and protein-rich food product, thereby serving as a nutritious food for detritus-feeding organisms. These are consumed by larger carnivorous forms.

Fungi and bacteria are key players in decomposition of the mangrove litters. Fungi are the first invaders, reaching their peak in the early phases of decomposition (Rajendran 1997). The tannins leach out of the litters and are degraded by fungi, but are toxic to bacteria (Steinke et al. 1990; Rajendran 1997; Rajendran and Kathiresan 1999b). After sufficient leaching of tannins from mangrove litter, bacteria colonize the litter and grow quickly with density ranging between 2×10^5 and 10×10^5 g^{-1} on *Kandelia candel* leaves that decomposed for 2–4 weeks, and this bacterial load is 100 times higher than actinomycetes and filamentous fungi (Zhuang and Lin 1993).

The azotobacters are nitrogen fixers, proliferating in decomposing the mangrove litter (Rajendran 1997), thereby increasing the nitrogen content of the mangrove litter by 2–3 times, especially after 6 weeks of litter decomposition (Chale 1993; Rajendran 1997; Wafar et al. 1997; Fig. 7.2). In the decomposing leaf, the C:N ratio reduces dramatically, due to increasing levels of nitrogen (Mann and Steinke 1992). The mangrove leaf litter attracts shrimp, crabs and fish, only after 4 weeks of decomposition when nitrogen is doubled due to microbial nitrogen fixation by azotobacters (Rajendran 1997; Rajendran and Kathiresan 1999a, b, 2004, 2007; Fig. 7.2).

The mangroves significantly contribute nutrients to the coastal food web. The nutrients that are released during litter decomposition help in proliferation of phytoplankton and heterotrophic microorganisms (Rajendran and Kathiresan 2004, 2007). Our further studies using stable isotopes of carbon and nitrogen in consumers and producers of a mangrove system reiterated the contribution of mangroves to the coastal food webs. Phytoplankton’s contribution to the food web increases with distance offshore. Hence, the detritus-based mangrove habitat supports a rich population of microbes by supplying nutrients from decomposing mangrove litter, which in turn support phytoplankton. This is consumed by zooplankton, small fishes and larger fishes, thereby operating the coastal food web (Nabeel et al. 2010; Fig. 7.3).

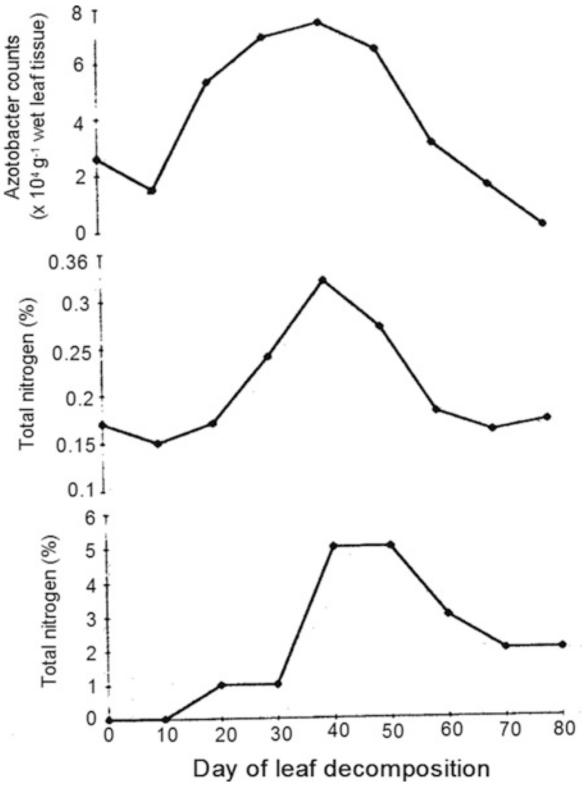

Fig. 7.2 Nitrogen-fixing azotobacter counts ($1 \times 10^4\ g^{-1}$), the total nitrogen content (%) and the juvenile prawns (no. $haul^{-1}$) associated with decomposing leaves of *Avicennia marina* for different days kept in nylon bags (35 cm × 35 cm. 2 mm mesh size) in mangrove waters (Rajendran 1997)

7.4 Polythene and Plastic-degrading Microbes

Mangrove-derived microbes do have ability of degrading the polythene and plastics. A bacterial species (*Pseudomonas* sp.) is capable of degrading 21% of polythene and 8% of plastics. A fungal species (*Aspergillus glaucus*) has an efficiency of degrading 29% of polythene and 7% of plastics (Kathiresan 2003). Therefore, studies on the microbial strains in clearing plastic wastes are progressing for their application in the field.

7.5 Dye Degradation by Mangrove-derived Microbes

Mangrove-derived microbes are efficient in dye degradation. Thraustochytrids (*Aplanochytrium* sp.) significantly removes the azo dye (malachite green) up to 86% within 5.5 days (Gomathi 2011). The cyanobacterium (*Synechococcus*

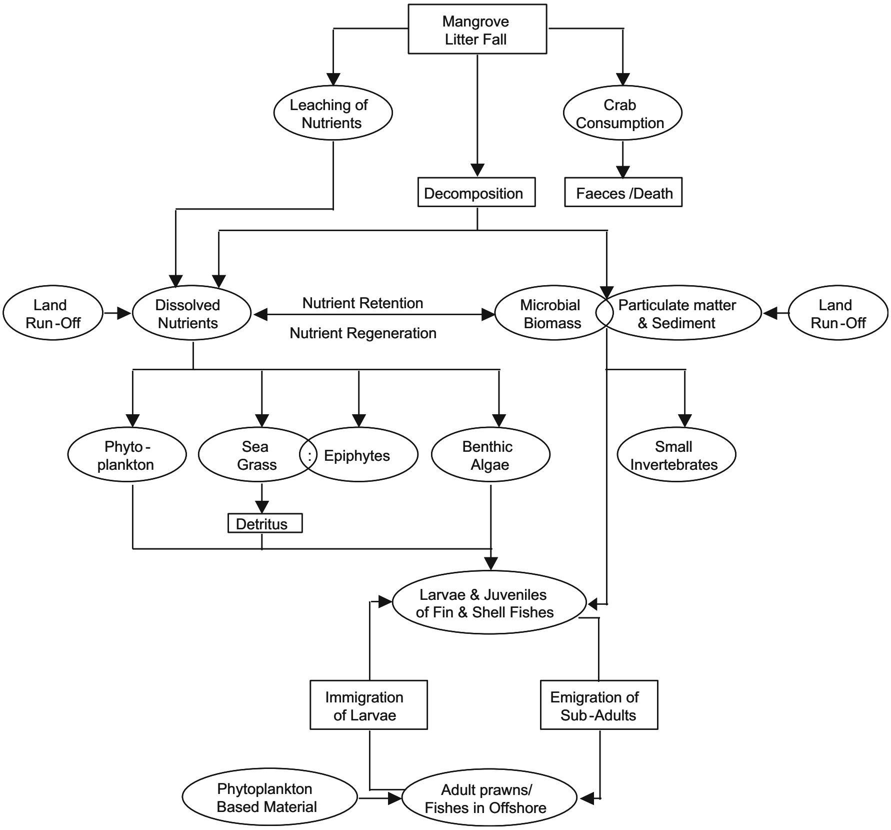

Fig. 7.3 Food web in a mangrove habitat (Kathiresan and Bingham 2001)

elongatus) degrades methyl red dye as much as 83% in 10 days (Anburaj 2011). About 89% of synthetic dye (malachite green) is known to be degraded by laccase enzyme derived from *Hypocrea lixii* within 10 days. The undegraded dye is highly toxic, while the degraded dye is nontoxic, as proved by biotoxicity assay with *Artemia salina* (Saravanakumar 2012).

7.6 Removal of Toxic Metals by Mangrove-derived Microbes

Mangrove habitats act as sink for toxic heavy metals due to the presence of microbes that are efficient in accumulation of toxic heavy metals. For example, the dried biomass of cyanobacterium (*Synechococcus elongatus)* removes Pb by 86% in sewage water within 60 minutes (Anburaj 2011). Similarly, the marine cyanobacterium (*Gloeocapsa* sp.) is efficient to remove calcium and cadmium up to 93% from seawater (Anburaj et al. 2011). Dried fungal biomass of *Aplanochytrium* sp. removes the toxic chromium by 69% in wastewater treatment (Gomathi et al. 2012). Similarly, the mangrove-derived *Trichoderma* biomass is efficient to remove the heavy metals. The fungal dry biomass of *Hypocrea lixii* removes 94% of Pb within 47 min and 88% of iron within 34 min (Saravanakumar 2012).

7.7 Bioprospecting Microbes from Mangroves

7.7.1 Antibiotic-Resistant Genes in Mangrove Sediments

Mangrove soil sediments are known to be rich in antibiotic-resistant genes, as reported in Sundarbans mangroves and Kerala (Bhattacharyya et al. 2018; Imchen et al. 2018a, b). The prevalence of antibiotic-resistant genes is in positive correlation with the contents of heavy metals and polyaromatic hydrocarbons in the soil. Multidrug-resistant bacteria (MDRB) are known to be highly salt tolerant with good growth at the level of salinity ranging between 12 and 21%. The antibiotic-resistant genes found in the mangrove soils can have serious effects if they become virulent as human pathogens. On the other hand, the heavy metal resistance genes can be used in developing transgenic organisms towards bioremediation applications (Bhattacharyya et al. 2018; Imchen et al. 2018a, b).

7.7.2 Mangrove-derived Enzymes

Mangrove habitat is a rich source of microbial enzymes (Kathiresan 2000a; Gupta et al. 2007). Our laboratory has proved the potential of the fungus *Penicillium fellutanum* isolated from mangrove sediment to produce enzymes such as glucose oxidase, amylase, cellulase, glucose isomerase and alkaline protease (Manivannan and Kathiresan 2007a, b; Kathiresan and Manivannan 2006a, b, c). These enzymes are commercially important. Glucose oxidase has practical application in food industries and clinical sectors (Richter 1983). Starch-degrading amylase is of great importance in food, fermentation, textile and paper industries (Lin et al. 1997). Cellulase finds application in bio-bleaching of pulp, treatment of wastewater and recycling of waste paper in pulp industries (Kang et al. 2004). Glucose isomerase is useful in production of sweetener, as an alternative to sugar (Aunstrup et al. 1979). Alkaline protease is primarily used as detergent additive, holding more than 50% of total enzyme market (Godfrey and Reichet 1985). The enzyme adenosine deaminase is produced by a bacterial endophyte *Lysinibacillus* sp. of the mangrove species, *Avicennia marina*, and this enzyme finds its application in disease diagnosis (Kathiresan et al. 2012).

The marine yeasts of mangrove soil are efficient in the production of invertase enzyme of industrial importance for converting the sucrose into glucose and fructose and glucosidase of antidiabetic effect for digesting the carbohydrates and processing the glycoproteins and lipids. The yeast extract can also serve as immunostimulator for increasing total haemocytes, phenoloxidase and endobiotics in haemolymph of the shrimp exposed to pathogenic vibrios (Manivannan 2008).

Among the microbes, *Trichoderma* species are much efficient in producing enzymes such as amylase, cellulase, protease, lipase and chitinase. These enzymes are important for litter decomposition process to occur in mangrove systems (Kathiresan et al. 2010). The protease derived from *Trichoderma estonicum* is capable of removing blood stain by 60% instantly, which is greater than that of the commercial detergent (Saravanakumar and Kathiresan 2012). Thermostable cellulase derived from *Trichoderma* (*Hypocrea estonica*) is a potent enzyme for the conversion of the lignocellulosic waste (sawdust) into the simple sugars (Saravanakumar 2012).

7.8 Other Derivatives from Marine Microbes

7.8.1 Marine Bacteria

The bacteria derived from the sediment around root system of mangroves are capable of (i) fixing nitrogen, (ii) solubilizing phosphate, (iii) producing ammonia and (iv) synthesizing plant growth hormone (IAA) (Kathiresan and Masilamani Selvam 2006). These bacteria are *Azotobacter vinelandii* and *Bacillus megaterium*, and they increase by twofold the growth of mangrove seedlings. Similarly *Azotobacter beijerinckii* improves the growth characteristics better in the mangrove seedlings of *Avicennia marina* and *Ceriops decandra* preferably at high salinity level of 30 g l^{-1}. This raises the possibility of using the marine bacteria as microbial biofertilizers (Ravikumar et al. 2004, 2007).

The marine lactobacilli isolated from mangrove sediment inhibit histamine-producing bacteria that are responsible for spoilage of fishes. This antibacterial activity is due to protein, namely, ‘bacteriocin’ with low molecular weight of 12 kDa produced by the lactobacilli. The bacteriocin is promising for its use as a marine fish preservative (Thiruneelakandan 2008). These bacteria are reported to have probiotic effects. For instance, *Paenibacillus* spp., *P. polymyxa* and Bacillus *cereus* are proved to be probionts against the vibrios, which are pathogenic to shrimp larvae (Ravi et al. 2007).

7.8.2 Marine Fungi

The fungus *Trichoderma* isolated from mangrove soil is capable of phosphate solubilization and phytase enzyme production. It is also proved that the fungal treatment improves the mangrove soil fertility as well as growth and biomass production of seedlings of *Avicennia marina* (Saravanakumar et al. 2013). Our laboratory has also proved the potential of mangrove-derived fungi in nutraceuticals, artificial honey bioethanol production and nanoparticle synthesis.

7.8.2.1 Nutraceuticals

Docosahexaenoic acid (DHA) is a polyunsaturated fatty acid (PUFA), essential for its functions in the brain and retina of humans and also in animal nutrition. The commercial source of DHA today is fish and fish oils. Because of low level of DHA in fish oil, the large-scale productions of DHA are difficult. However, thraustochytrids have a potential for commercial utility in nutraceutical sectors. DHA production by the thraustochytrids (*Aplanochytrium* sp.) is found to be the maximum in culture medium containing yeast powder (8.35 mg l^{-1}), maida powder (6.32 mg l^{-1}), vitamin C 10.08 mg l^{-1} and vitamin B 12.08 mg l^{-1} (Gomathi 2009; Gomathi et al. 2013), and hence the thraustochytrids are being attempted for mass scale cultivation, as a commercial source of polyunsaturated fatty acids.

7.8.2.2 Artificial honey using yeasts

Honey bees are abundant in the mangrove habitats especially of Sundarbans, and they make honey of high medicinal value. Honey collection, known as apiculture, is a potential livelihood for many mangrove-dependent people. The sweetness of honey is mainly due to the presence of fructose. The honey bees used to collect nectar from the flowers and mix it vigorously with their saliva. During this process, the fructose is released from sucrose solution of the plant nectar, and honey is then produced. We have isolated the yeast cells from the salivary glands of the honey bee, *Apis cerana*, and inoculated in sucrose solution under agitation in laboratory conditions. The solution exhibits increased levels of fructose and total amino acids. The solution after 48 h becomes brown in colour, similar to the natural honey. Our laboratory has made a breakthrough in production of artificial honey using yeast cells (Kathiresan and Srinivasan 2006).

7.8.2.3 Bioethanol production using yeasts

Our laboratory has proved that mangrove-derived marine yeast strains (*Saccharomyces cerevisiae* and *Pichia salicaria*) are promising for bioethanol production over the terrestrial yeast (Kathiresan and Saravanakumar 2011; Saravanakumar et al. 2013). *Candida albicans* exhibits a high ethanol production (47.3 ± 3.1 g/L) within 96 h, when glucose is used as carbon source. This species produces increased level of bioethanol when the yeast cells are immobilized in sodium alginate (Senthil Raja and Kathiresan 2011). Sawdust, a lignocellulosic waste material, can be used for achieving the bioethanol production of up to 85.6% (55.2 g l^{-1}) under the optimized conditions of temperature of 36.5 °C, incubation hours of 102 h, hydrolysed sawdust of 45.14 ml l^{-1} and agitation of 330 rpm (Saravanakumar and Kathiresan 2012, 2014). Work on ethanol production by using marine-derived yeasts is at progress for its application.

7.8.2.4 Nanoparticle synthesis

Marine microorganisms are capable of inducing the nanoparticles synthesis. *Escherichia coli* and *Aspergillus niger* isolated from mangrove soil are efficient in reducing the silver ions to nanoparticles at a faster rate. The silver nanoparticles inhibit human pathogenic bacteria and fungi. The yeast *Pichia capsulata* produces silver nanoparticles, within minutes. The yeast protein with molecular weight of 70 kDa is responsible for nanoparticle synthesis (Kathiresan et al. 2010). *Penicillium fellutanum* isolated from mangrove soil is also capable of producing silver nanoparticles within minutes (Kathiresan et al. 2009). Similarly mangrove-derived fungi (*Trichoderma hamatum*, thraustochytrids) and cyanobacteria exhibit the synthesis of silver and gold nanoparticle (Gomathi 2009, 2011; Anburaj 2011; Saravanakumar 2012). The mangrove-based nanoparticles possess different biological activities such as inhibiting the human pathogenic bacteria and controlling the vibriosis, a common shrimp disease (Kathiresan et al. 2012). The use of nanoparticles is proved in stabilizing the cotton fabrics and making them odour resistant, preserving the apple fruits, purifying the drinking water from microbial contaminants, detoxifying the carcinogenic ethidium bromide as well as in killing the cancer cells that cause oral and skin cancers (Asmathunisha and Kathiresan 2013).

7.8.3 Marine Actinomycetes

Streptomyces species isolated from mangrove soil are capable of producing alkaline protease (Kathiresan and Manivannan 2007), and they are capable of inhibiting fungal pathogens which cause crop diseases (Kathiresan et al. 2005). Gutingimycin is a highly polar trioxacarcin derivative extracted from a *Streptomyces* species of the Laguna de Terminos, Gulf of Mexico (Maskey et al. 2002). This species also yields trioxacarcins A-C, D-F3-5 (Maskey et al. 2002). Marine actinomycetes belonging to the family *Micromonosporaceae* are potent source of anticancer agents.

7.8.4 Marine Microalgae

Many algae can convert simple polyunsaturated fatty acids like arachidonic acid (Gerwick et al. 1994). Derivatives of arachidonic acids are capable of maintaining homeostasis in mammals and in controlling abnormal production of metabolites during human diseases such as cancer, heart disease, arteriosclerosis, ulcers, psoriasis and asthma. Marine microbes are the potential source of bioactive substances as evident by increasing numbers of compounds and their patents (Tables 7.3 and 7.4).

7.9 Concluding Remarks

Mangroves are genetic paradise especially for salt-tolerant microbes that remain unexplored. In order to survive in varied physico-chemical conditions of mangrove habitats, the microbes are forced to synthesis a number of biologically active substances with novel structures. Potentials of these substances are increasingly known only in the recent past. However, an intensive search for antibiotics from

Table 7.3 Some of patented marine compounds (Ocean Drug Alert, Lucknow, Vol.10–17)

Organism	Compound	Activity	Assignee	Year
Blue-green algae	Crude extract	Trafficking or homing of stem cells	Texinfine SA	2001
Bacterium *Alcaligenes faecalis*	Crude extract	Antibacterial agent	University of South Carolina	2001
Marine yeast	B-1,3-Glucan	Anticancer	Orient cancer therapy	2003
Marine actinomycetes	Indole carbazole alkaloids	Mammalian cancer cell lines	Institute of Biomarine SA Spain	2005
Microbes – parasitic to seaweeds	Isochroman compound pseudodeflectusin	Anticancer	Nippon Kayaku Kabushiki Kaisha, Tokyo, Japan	2005
Marine actinomycetes	Certain fermentation products	Antineoplastic agents	The Regents of the University of California, USA	2005

Table 7.4 Bioactive compounds derived from marine microbes (Kathiresan et al. 2008)

Species	Bioactivity and compounds	Reference
Lyngbya majuscula (cyanobacteria)	Anti-inflammatory substances (debromoaplysiatoxin and Lyngbyatoxin-A)	Cardillina et al. (1979)
Prorocentrum spp. (dinoflagellates)	Okadaic acid is protein phosphatase inhibitor molecule, used to trace signal transduction pathways in eukaryotic cells	Cohen et al. (1990)
Lyngbya majuscula	Microcolin A is inhibiting two-way murine mixed lymphocyte reaction, at nanomolar	Koehn *et al.* (1992)
Cyanobacterial species	Scytonemin is a sheath pigment that has recently been patented as an anti-inflammatory agent	Proteau et al. (1993)
Lyngbya majuscula	Curacin A has antitumor activity in vitro by inhibiting microtubule assembly by binding at the colchicine site; the compound is yet to be successfully formulated for use in vitro	Gerwick et al. (1994)
Micromonospora marina (marine actinomycetes)	Antitumor	Baz et al. (1997)

marine microbes is felt necessary for treating the incurable diseases. However, there are two bottlenecks in the marine microbiological research: slow-growing microbes and unculturable microbes under laboratory conditions. Better culture techniques are to be developed to isolate slow-growing microbes, which may have better potential for producing high value metabolites. The unculturable microbes can be visualized for their potential metabolic and biochemical capabilities through the genome sequencing, and hence, it is quite possible to extract bioactive substances even from the non-culturable microbes. Intensive research is required on bioprospecting the marine microbes of mangrove ecosystems for a wide range of applications in agriculture, food preservation, waste management and in nanotechnology.

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Current Understanding of the Mangrove Forests of India

8

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Abstract

In this chapter the current understanding on various components of Indian mangrove habitats is reviewed and conservation measures required to ensure the sustainability of Indian mangroves are discussed. In India, mangroves are found on the east and west coasts of the mainland and on the Islands of Andaman and Nicobar and Lakshadweep. Indian mangroves represent 3.3% of global mangroves and about 56% of global mangrove species. Despite considerable

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work on the floristics and ecology of mangroves with minimal attention to management-related issues, Indian mangroves also remain underexplored in various other aspects—forest structure, faunal diversity, genetic diversity, soil physicochemical properties, microbial diversity, ecological services and its economic evaluation—which are prerequisites for effective implementation of conservation and management measures. Further, the bulk of the research has been carried out in the Indian Sundarbans, Bitharkanika, Pichavaram, and the Andaman and Nicobar Islands; other areas remain little studied. As we live in a world of diminished ecological diversity, the conservation focus on natural resources has shifted from species to ecosystems, and recent efforts have been focused on an ecosystem-based management approach. However, mangrove conservation measures have often relied on legal protection of existing mangroves and rehabilitation of degraded mangroves by monospecific plantation globally, as well as in India. Despite a recent increase in mangrove coverage and a slowdown in the degradation rate (judged solely on the basis of global or regional-scale remote sensing studies) achieved by existing conservation and rehabilitation measures, the ecological health of Indian mangroves, as well as mangroves in other countries, has experienced a continuous decline due to uncontrolled upstream anthropogenic activities and global climate change. National-level policy making in India lacks comprehensive understanding of how the various types of mangrove habitats along the coast function, in what social and ecological aspects they differ, and how those differences might be taken into account while planning for conservation. Since mangroves are highly dynamic and threatened, the understanding of various components and their interconnections is invaluable for streamlining future research and effective formulation of long-term, integrated, ecosystem-based management for preserving the biological diversity, ecological health, and ecological integrity of mangroves. Considering these facts, this chapter discusses the current knowledge on Indian mangroves on the basis of the available literature and future prospects for ecosystem-based management are also highlighted.

Keywords
Mangroves · Conservation · Ecosystem · Mangrove habitats · Anthropogenic activities · Biological diversity

8.1 Introduction

Mangroves comprise trees, shrubs, palms, herbs, or ferns, which are uniquely adapted to the harsh environmental conditions of the intertidal zone (Primavera et al. 2004). Their distribution in the tropics and subtropics (approximately between 32°N and 38°S) is encountered along the sea coast in backwater creeks and river estuaries between approximately midtide and the extreme high-water mark, depending upon the air temperature, ocean currents, protection, shallow shores, salt water, and soil types. The best mangrove formations are seen where the tidal regime is normal with constant mixing of seawater and freshwater and where the annual rainfall is more than 200 cm; optimally, the temperature does not go below 20 °C and usually the minimum temperature does not vary by more than 5 °C (Saenger et al. 1983). These conditions are more predominant on the eastern borders of continents. The restricted distribution is mainly due to the sensitivity of mangroves to frost and cold temperatures. They are the most threatened, as well as the most productive, coastal shoreline habitats of tropical and subtropical regions of the world (Tomlinson 2016; Spalding et al. 2010), and they are now expanding into temperate regions on multiple continents (Saintilan et al. 2014). Globally, mangroves cover an area of 137,760 km^2, spanning 118 countries and territories (Giri et al. 2011). Despite the significant ecological and economical services they provide, mangroves have experienced an annual loss of between 0.16% and 0.39%, globally, because of rapid coastal development (Hamilton and Casey 2016). In South Asia, mangrove forests have been lost at an average rate of 0.18% per year (Richards and Friess 2016). Growing anthropogenic activities and global climate change also threaten mangroves, and are on the edge of extinction. Thus, mangrove conservation needs to be prioritized globally.

In India, mangroves are found along the coastlines of nine states and four union territories (UTs) (Fig. 8.1), and are spread over an area of 4921 km^2, which represents 3.3% of global mangrove vegetation (FSI 2017). In contrast to global trends, mangrove coverage in India has increased significantly in the last decade. Estimates by the Forest Survey of India show a net increase of 875 km^2 during 1987–2017, with a mean annual increase in mangrove coverage of 30.21 ± 81.72 km^2; the extent of the increase was 112 km^2 between 2013 and 2015 and 181 km^2 between 2015 and 2017 (FSI 2017). However, the ecological health of mangroves globally, as well as in India, remains degraded, and implicit species loss has been witnessed despite mangrove expansion in many regions (Giri et al. 2008, 2015; Hamilton and Casey 2016). Further, as in other countries, information on Indian mangroves is highly scattered with knowledge gaps, which impeding successful implementation of conservation and management. For instance, core issues such as salinity tolerance and what constitutes a “true” mangrove still persist (Maxwell 2015).

The failure of many mangrove restoration programs in the last two decades, due to poor species selection, also confirms the lack of understanding on mangrove dynamics. This calls for evaluation of our understanding on mangrove dynamics and the effectiveness of existing conservation methods, and refinement of them for better management of mangroves. In this chapter, the knowledge on Indian mangroves is discussed in eight sections, which are primary requisites for better management, based on the available literature, and future prospects for site-specific conservation also highlighted.

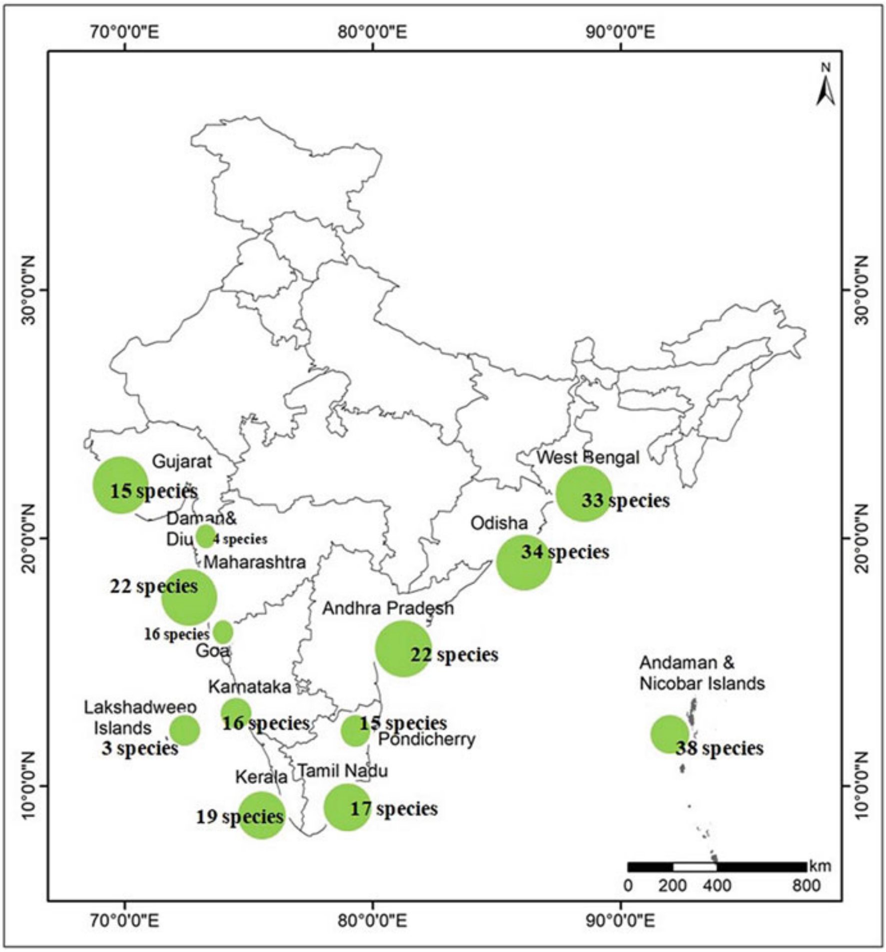

Fig. 8.1 Distribution of mangrove habitats on the Indian coast and state/union territory–wise species richness

8.2 Species Composition and Distribution

The species is a fundamental unit of an ecosystem. In general, in comparison with other tropical ecosystems, mangroves are species poor (Duke 2017), so the loss of a single species is of great concern in mangroves (Polidoro et al. 2010). Thus, knowledge of species composition and distribution is a fundamental prerequisite for effective conservation and management of mangroves. In the past, the species composition and distribution of mangroves globally has been reviewed by many researchers (e.g., Saenger et al. 1983; Tomlinson 1986; Ricklefs and Latham 1993; Duke 1992; Field 1995; Duke et al. 1998a, b; Ellison et al. 1999; Saenger 2002;

Wang et al. 2003; Spalding et al. 2010; Polidoro et al. 2010). At present, the updated list of true mangrove species of the world consists of 82 species (including 11 natural hybrids) in 30 genera from 17 families worldwide (Table 8.1). However, uncertainty also surrounds the number of mangrove species found globally. The issue of exactly what constitutes a mangrove still persists because of disparities in the attempt to assign "true" versus "associate" status to many mangroves (Maxwell 2015). For instance, Duke (2017), in his recent biogeography of mangroves, excluded certain species: *Acanthus volubilis*, *Acanthus xiamenensis*, *Phoenix paludosa*, *Brownlowia argentata*, *Heritiera globosa*, *Aglaia cucullata*, and *Excoecaria indica.* With the exception of *Heritiera globosa*, all of these species are retained in this text, as they constitute important vegetation in mangroves of Indo-Malesia. *Heritiera globosa*, which was considered a mangrove species in the past (Duke 1992; Giesen et al. 2006), is excluded from this text, as it has been found only at the upper reaches of rivers in Borneo, where the water is always fresh, which is consistent with the classification by Duke (2017). Further, certain species—*Muellera moniliformis*, *Barringtonia racemosa*, *Crenea patentinervis*, *Pavonia paludicola*, and *Pavonia rhizophora*—were ranked as mangroves for the first time by Duke (2017), but the reasons for the inclusion of these were not discussed. So, those species are not considered here. Similarly, *Rhizophora* × *beristyla* is also not included in this text, as it was considered a synonym of *R. mangle* (Hou 1960; Breteler 1977) and later it was lectotypified as a synonym of *R.* × *harrisonii.*

Indian mangroves represent 46 true mangrove species (42 species and four natural hybrids) belonging to 14 families and 22 genera. State/union territory–wise species composition is given in Table 8.2. The mangrove habitat of India is broadly divided into three types: deltaic mangroves (eastern coast mangroves), estuarine and backwater mangroves (western coast mangroves), and insular mangroves (those of the Andaman and Nicobar Islands) (Mandal and Naskar 2008). Of these three, the mangroves of the Andaman and Nicobar Islands have been studied most extensively (Dagar 1982, 1995, 1998, 2003; Dagar et al. 1991, 1993) and recently by Goutham-Bharathi et al. (2014) and Ragavan 2015). A total of 38 mangrove species in the Andaman and Nicobar Islands, belonging to 13 families and 19 genera, have been documented (Ragavan 2015). Significant findings of these studies are four new records for India (*Sonneratia lanceolata*, *S. ovata*, *S.* × *urama*, and *S.* × *gulngai*), two new distribution records for the Andaman and Nicobar Islands (*Excoecaria indica* and *Rhizophora* × *annamalayana*), and rediscovery of three species (*Sonneratia griffithii*, *Brownlowia tersa*, and *Acanthus volubilis*) after a lapse of 90 years. In addition, a critical analysis of *Rhizophora* species has revealed the occurrence of a hybrid between *R. mucronata* and *R. stylosa* (*R.* × *mohanii*) and two new entities (*Rhizophora stylosa* var. *andamanica* (an advanced stage of hybridization between *R. mucronata* and *R. stylosa*) and *R. mucronata* var. *alokii*). A hybrid between *Acrostichum aureum* and *Acrostichum speciosum* has also been identified. Earlier, many workers (Saenger et al. 1983; Dagar 1982, 2003; Dagar et al. 1991) included *Acrostichum aureum*, *A. speciosum*, *Aglaia cucullata*, *Brownlowia tersa*, and *Dolichandrone spathacea* in the list of associate mangrove species. Furthermore, incorrect reports on occurrences of species (*Avicennia alba*,

Table 8.1 Mangrove species of the world

Family	Genus	Species[a]
Acanthaceae	*Acanthus*	*Acanthus ebracteatus*
		Acanthus ilicifolius
		Acanthus volubilis
		Acanthus xiamenensis
Avicenniacea	*Avicennia*	*Avicennia alba*
		Avicennia bicolor[b]
		Avicennia germinans[b]
		Avicennia schaueriana[b]
		Avicennia integra
		Avicennia marina
		Avicennia officinalis
		Avicennia rumphiana
Arecaceae	*Nypa*	*Nypa fruticans*
	Phoenix	*Phoenix paludosa*
Bignoniaceae	*Dolichandrone*	*Dolichandrone spathacea*
	Tabebuia	*Tabebuia palustris*[b]
Combretaceae	*Conocarpus*	*Conocarpus erectus*[b]
	Laguncularia	*Laguncularia racemosa*[b]
	Lumnitzera	*Lumnitzera littorea*
		Lumnitzera racemosa
		Lumnitzera × *rosea*
Ebenaceae	*Diospyros*	*Diospyros littorea*
Euphorbiaceae	*Excoecaria*	*Excoecaria agallocha*
		Excoecaria indica
		Excoecaria ovalis
Fabaceae	*Cynometra*	*Cynometra iripa*
	Mora	*Mora oleifera*[b]
Lythraceae	*Pemphis*	*Phemphis acidula*
	Sonneratia	*Sonneratia alba*
		Sonneratia apetala
		Sonneratia caseolaris
		Sonneratia griffthii
		Sonneratia lanceolata
		Sonneratia ovata
		Sonneratia × *gulngai*
		Sonneratia × *urama*
		Sonneratia × *hainanensis*
Malvaceae	*Brownlowia*	*Brownlowia argentea*
		Brownlowia tersa
	Camptostemon	*Camptostemon philippinensis*
		Camptostemon schultzii
	Heritiera	*Heritiera fomes*
		Heritiera littoralis

(continued)

Table 8.1 (continued)

Family	Genus	Species[a]
Meliaceae	*Aglaia*	*Aglaia cucullata*
	Xylocarpus	*Xylocarpus granatum*
		Xylocarpus moluccensis
Primulaceae	*Aegiceras*	*Aegiceras corniculatum*
		Aegiceras floridum
Myrtaceae	*Osbornia*	*Osbornia octodonta*
Plumbaginaceae	*Aegialitis*	*Aegialitis annulata*
		Aegialitis rotundifolia
Pteridaceae	*Acrostichum*	*Acrostichum aureum*[c]
		Acrostichum danaeifolium[b]
		Acrostichum speciosum
Rhizophoraceae	*Bruguiera*	*Bruguiera cylindrica*
		Bruguiera exaristata
		Bruguiera hainesii
		Bruguiera gymnorhiza
		Bruguiera parviflora
		Bruguiera sexangula
		Bruguiera × *rhynchopetala*
	Ceriops	*Ceriops australis*
		Ceriops decandra
		Ceriops pseudodecandra
		Ceriops tagal
		Ceriops zippeliana
	Kandelia	*Kandelia candel*
		Kandelia obovata
	Rhizophora	*Rhizophora apiculata*
		Rhizophora mangle[b]
		Rhizophora samoensis[c]
		Rhizophora mucronata
		Rhizophora racemosa[b]
		Rhizophora stylosa
		Rhizophora × *lamarckii*
		Rhizophora × *annamalayana*
		Rhizophora × *mohanii*
		Rhizophora × *selala*
		Rhizophora × *tomlinsonii*
Rubiaceae		*Rhizophora* × *harrisonii*[b]
Tetrameristaceae	*Scyphiphora*	*Scyphiphora hydrophylacea*
	Pelliciera	*Pelliciera rhizophorae*[b]

[a] × indicates a hybrid

[b] Present in Atlantic–East Pacific mangroves

[c] Present in both Atlantic–East Pacific and Indo-West Pacific mangroves

Table 8.2 Distribution of true mangrove species in mangrove habitat of India

	Occurrence[a]													Status[b]	
Species	WB	OD	AP	TN	PC	KR	GA	GU	KL	MA	LA	DD	ANI	Global	In India
Acanthaceae															
Acanthus ebracteatus Vahl		?			•				•?				•	LC	EN
Acanthus ilicifolius L.	•	•	•	•	•	•	•	•	•	•		•	•	LC	LR
Acanthus volubilis Wall.	•	•											•	LC	NA
Avicennia alba Blume	•	•	•		•	•	•	•	?	•			?	LC	LR
Avicennia marina (Forssk.) Vierh	•	•	•	•	•	•	•	•	•	•	?	•	•	LC	LR
Avicennia officinalis L.	•	•	•	•	•	•	•	•	•	•			•	LC	LR
Arecaceae															
Nypa fruticans (Thunb.) Wurmb	•	?							?				•	LC	EN
Phoenix paludosa Roxb.	•	•											•	NT	NA
Bignoniaceae															
Dolichandrone spathacea (L.f.) Baill. ex Schumann	•	•							•	•			•	LC	VU
Combretaceae															
Lumnitzera littorea (Jack.) Voigt													•	LC	EN
Lumnitzera racemosa Willd.	•	•	•	•	•	•	•	•	•	•			•	LC	LR
Euphorbiaceae															
Excoecaria agallocha L.	•	•	•	•	•	•	•	•	•	•			•	LC	LR
Excoecaria indica (Willd.) Muell.-Arg.	•	•							•				•	DD	EN
Fabaceae															
Cynometra iripa Kostel.	•	•								•			•	LC	VU
Lythraceae															
Pemphis acidula J.R. Forst.				•							•		•	LC	VU
Sonneratia alba Sm.	•	•	•			•	•		•	•			•	LC	VU

Sonneratia apetala Buch.-Ham.	•	•	•	•?	•		?	•	?	•		•	?	LC	VU
Sonneratia caseolaris (L.) Engl.	•	•				•	•		•	•			•	LC	VU
Sonneratia griffithii Kurz.	?	?											•	CR	EN
Sonneratia lanceolata Blume													•	LC	NA
Sonneratia × *urama* N.C. Duke													•	NA	NA
Sonneratia × *gulngai* N.C. Duke													•	NA	NA
Sonneratia ovata Backer													•	NT	NA
Malvaceae															
Brownlowia tersa (L.) Kosterm.	•	•	•										•	NT	NA
Heritiera fomes Buch.-Ham	•	•												EN	VU
Heritiera littoralis Dryand.		•							?	•			•	LC	VU
Meliaceae															
Aglaia cucullata (Roxb.) Pellegr.	•	•											?	DD	NA
Xylocarpus granatum J. Koenig	•	•	•	•?			?			•			•	LC	VU
Xylocarpus moluccensis (Lam.) M. Roem.	•	•	•	•	•								•	LC	VU
Myrsinaceae															
Aegiceras corniculatum (L.) Blanco	•	•	•	•	•	•	•	•	•	•		•	•	LC	LR
Plumbaginaceae															
Aegialitis rotundifolia Roxb.	•	•	•										?	NT	VU
Pteridaceae															
Acrostichum aureum L.	•	•	•	•?		•	•		•	•			•	LC	LR
Acrostichum speciosum Willd.		•											•	LC	EN
Rhizophoraceae															
Bruguiera cylindrica (L.) Blume	•	•	•	•	•	•	•	•	•	•	•		•	LC	LR
Bruguiera gymnorrhiza (L.) Lam.	•	•	•		•	•	•	•	•	•			•	LC	LR

(continued)

Table 8.2 (continued)

Species	Occurrence[a]													Status[b]	
	WB	OD	AP	TN	PC	KR	GA	GU	KL	MA	LA	DD	ANI	Global	In India
Bruguiera parviflora Wight & Arn. ex Griff.	•	•							?	•	?		•	LC	VU
Bruguiera sexangula (Lour.) Poir.	•	•							•				?	LC	VU
Ceriops decandra (Griff.) Ding Hou	•	•	•	•		•		•					?	NT	VU
Ceriops tagal (Perr.) C.B. Rob.	•	•	•	•	•		•	•	•	•	•		•	LC	VU
Kandelia candel (L.) Druce	•	•	•			•	•	•	•	•			?	LC	LR
Rhizophora apiculata Blume	•	•	•	•	•	•	•	•?	•	•			•	LC	LR
Rhizophora mucronata Lam.	•	•	•	•	•	•	•	•	•	•			•	LC	LR
Rhizophora stylosa Griff.		?											•	LC	EN
Rhizophora × *annamalayana* Kathiresan				•									•	NA	EN
Rhizophora × *lamarckii* Montrouz													•	NA	EN
Rubiaceae															
Scyphiphora hydrophylacea C.F. Gaertn	•	•	•										•	LC	EN
Species	33	34	22	17	15	16	16	15	19	22	3	4	38		
Genera	21	20	15	12	10	11	11	10	12	15	3	4	19		
Family	14	14	11	8	7	7	7	6	8	11	2	3	13		

Revised on the basis of Ragavan et al. (2016)

ANI Andaman and Nicobar Islands, *AP* Andhra Pradesh, *CR* critically endangered, *DD* data deficient, *DU* Daman and Diu, *EN* endangered, *GA* Goa, *GU* Gujarat, *KL* Kerala, *KR* Karnataka, *LA* Lakshadweep, *LC* least concern, *LR Lower risk*, *MA* Maharashtra, *NA* not assessed, *NT* near threatened, *OD* Odisha, *PC* Puducherry, *TN* Tamil Nadu, *VU* vulnerable, *WB* West Bengal

[a] • denotes occurrence, •? denotes occurrence not found in recent times,? denotes occurrence not confirmed

[b] Global status as per Polidoro et al. (2010); status in India as per Kathiresan (2008)

Aegialitis rotundifolia, *Aglaia cuculata*, *Bruguiera sexangula*, *Ceriops decandra*, *Kandelia candel*, and *Sonneratia apetala*) in the Andaman and Nicobar Islands have also been noted.

The mangrove coverage is larger and more widespread on the east coast than on the west coast because of its distinctive geomorphological setting. Overall, mainland India has 40 mangrove species belonging to 14 families and 22 genera. All 40 species are known on the east coast, whereas the west coast has only 27 species belonging to 11 families and 16 genera (Ragavan et al. 2016). Species such as *Scyphiphora hydrophylacea*, *Rhizophora* × *annamalayana*, *R. stylosa*, *Acrostichum speciosum*, *Aegialitis rotundifolia*, *Aglaia cucullata*, *Heritiera fomes*, *Brownlowia tersa*, *Pemphis acidula*, *Nypa fruticans*, *Phoenix paludosa*, and *Acanthus volubilis* are restricted to the east coast in mainland India. None of the species are unique to the west coast of India. Despite extensive studies on floristics and ecology, the species identity and distribution of the mangroves of mainland India still remain elusive. For instance, the identity and distribution of *Sonneratia griffithii* in the Sundarbans and Odisha are doubtful, as are those of *Acanthus ebracteatus* in Kerala and Odisha. The distributions of *Avicennia alba* in Kerala and *Rhizophora stylosa* in Odisha are not clear. Further, certain species such as *Aglaia cucullata* have not been found in the field for more than a decade. A few recent site-specific floristics studies on the mangroves of Kerala, Odisha, the Sundarbans, and Maharashtra have provided additional information on mangrove flora in India. Mohandas et al. (2014) and Lovly and Merlee-Teresa (2016) reported the occurrence of *Nypa fruticans* on the Kerala coast. Though photographs were provided by them, information on voucher specimens and a taxonomic description was not given. It is pertinent to note that the presence of *N. fruticans* on the Malabar coast was listed by Van Rheede (1678–1693) in his classical work *Hortus Indicus Malabaricaus*. So, the presence of *N. fruticans* in Kerala needs to be validated through exclusive surveys. Similarly, Chavan (2013) and Panda et al. (2017) reported the presence of *Bruguiera parviflora* and *Acanthus volubilis* in Maharashtra and Odisha, respectively, but both reports lacked clear evidence.

In a few studies, species have been identified incorrectly. For instance, Pradhan et al. (2016) and Panda et al. (2017) reported the occurrence of *A. ebracteatus* in Bhitarkanika, but from a flower image with a prominent bract and bracteoles, it is well understood that the white color form of *A. ilicifolius* was misidentified as *A. ebracteatus*. Debnath et al. (2013) reported a new mangrove species, *Acanthus albus*, from the Sundarbans. This new species is like *A. ilicifolius* except in its flower color and has smaller leaves, fruit, and flowers. A similar kind of specimen was reported from Sri Lanka by Liyanage (1997) as *A. volubilis*; later it was confirmed as a whitish lowered form of *A. ilicifolius* (Jayatissa et al. 2002). Similarly, reports of *Cynometra ramiflora* and *Sonneratia griffithii* from the Indian Sundarbans and the Odisha coast have been found to be misidentification of ecological variants of *Cynometra iripa* and *Sonneratia alba* (Ragavan et al. 2017; Kathiresan 2018) respectively, and the occurrence of *Rhizophora stylosa* in Odisha also remains doubtful.

India is the third most mangrove species–rich country in the world, after Indonesia and Australia (Ragavan et al. 2016). However, the species diversity of

Indian mangroves is under constant flux due to both natural forces (e.g., erosion, aggradations) and anthropogenic forces, possibly leading to changes in floristic composition and local extinction of some species. With the exceptions of *Avicennia marina* and *Excoecaria agallocha*, all mangrove species are at varying degrees of threat in India, with about 52% of species having low abundance and restricted distribution, while nine species are of conservation significance at a global level: *Sonneratia griffithii* and *Heritiera fomes* are "critically endangered", *Excoecaria indica* and *Aglaia cucullata* are "data deficient", and *Aegialitis rotundifolia*, *Brownlowia tersa*, *Ceriops decandra*, *Phoenix paludosa*, and *Sonneratia ovata* are "near threatened" (Polidoro et al. 2010; Figs. 8.2 and 8.3). Further, certain mangrove species (*Heritiera littoralis*, *Xylocarpus granatum*, *Bruguiera cylindrica*, *Lumnitzera racemosa*, *Sonneratia caseolaris*, and *Cynometra iripa*) are on the verge of extinction on the west coast (Chavan 2013), and the populations of *Aglaia cuculata*, *Brownlowia tersa*, *Heritiera fomes*, *Kandelia candel*, *Nypa fruticans*, and *Xylocarpus molluccensis* have declined dramatically in the Indian Sundarbans (Mukhopadhyay et al. 2018) along the east coast. Selvam (2003) did not observe *Xylocarpus granatum*, *Sonneratia apetala*, *Kandelia candel*, and *Bruguiera gymnorhiza* in Pichavaram mangroves, which had been observed two decades earlier in the region. In recent times, the mangrove floristics of mainland India have not been explored sufficiently; thus, extensive floristics studies are needed to confirm the correct identity and distribution of mangroves in the east and west of India. Furthermore, efforts need to be taken to increase the population of species that are at risk of extinction or are of low abundance.

8.3 Forest Structure

The biodiversity and ecosystem functioning of mangroves are determined by the forest structure (Soares 1999; Cavalcanti et al. 2009). Information on the forest structure is the primary database that provides insight into the specific feature of each mangrove ecosystem. The forest structure of mangroves is controlled more by local site factors—including topography, soil properties, and tide fluctuations (Smith 1992; Kauffman and Cole 2010)—than by climatic factors such as rainfall and temperature, which control the worldwide distribution of mangroves. Thus, mangrove stands exhibit wide regional and local variations in their structural characteristics. Hence, local-level understanding of the forest structure is essential for their management. Furthermore, understanding of the structural characterization of vegetation is a valuable tool for investigation of the responses of mangrove ecosystems to current environmental conditions and environmental change processes, thereby aiding in their conservation (Soares 1999; Estrada et al. 2013).

The forest structure of mangroves is relatively simple in comparison with other forest types, such as tropical rain forests. Lack of understory and presence of zonation is often described as unique feature of mangrove forest. The combination of salinity, flooding stresses, and low light levels accounts for the lack of an understory in mangroves (Janzen 1985; Lugo 1986), whereas various biotic and abiotic factors

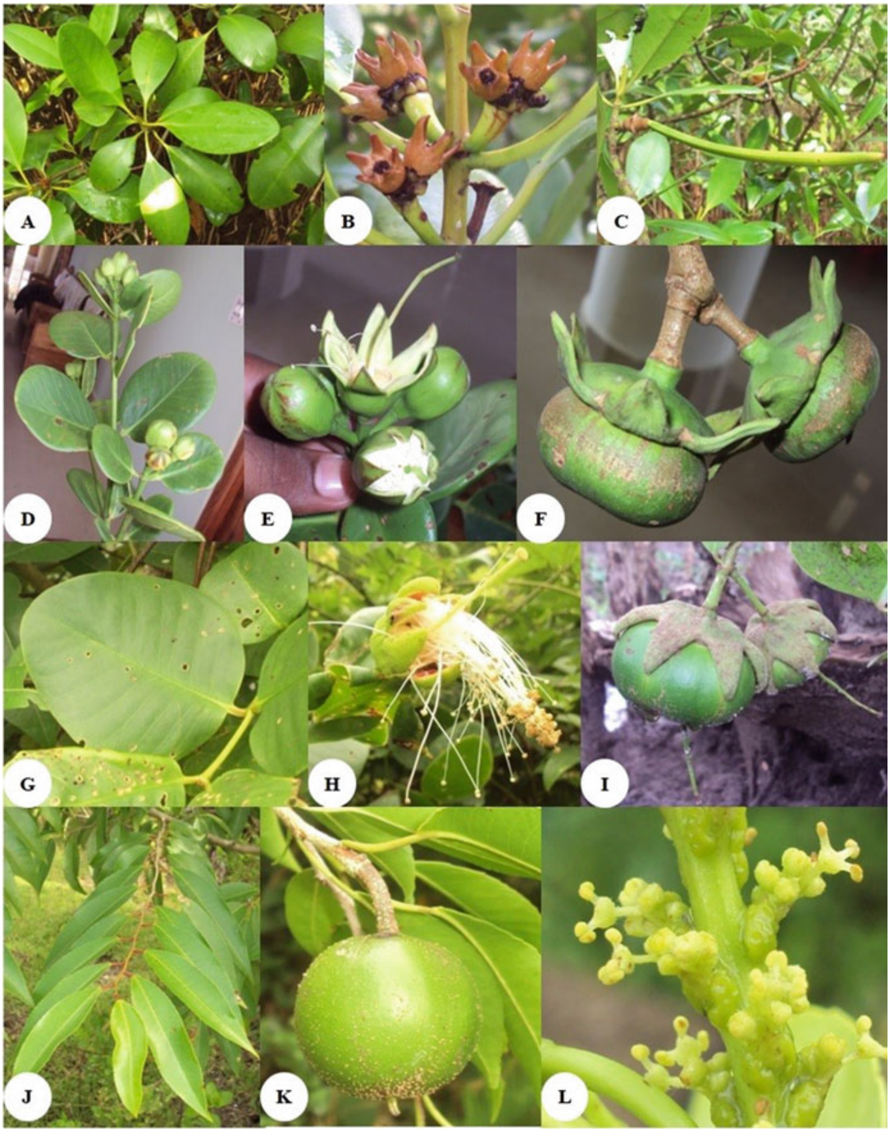

Fig. 8.2 Threatened true mangrove species of India. (**a**–**c**) *Ceriops decandra*. (**d**–**f**) *Sonneratia griffithii*. (**g**–**i**) *Sonneratia ovata*. (**j**–**l**) *Excoecaria indica*

influence the zonation pattern (Bernini and Rezende 2011). The forest structure of mangroves is often characterized by attributes such as species richness (including associate species), canopy height, basal area, tree density, and age/size class distribution (Oliver and Larson 1996). These measures of the forest structure are one way to evaluate the development or maturity of a forest ecosystem, and they are also used

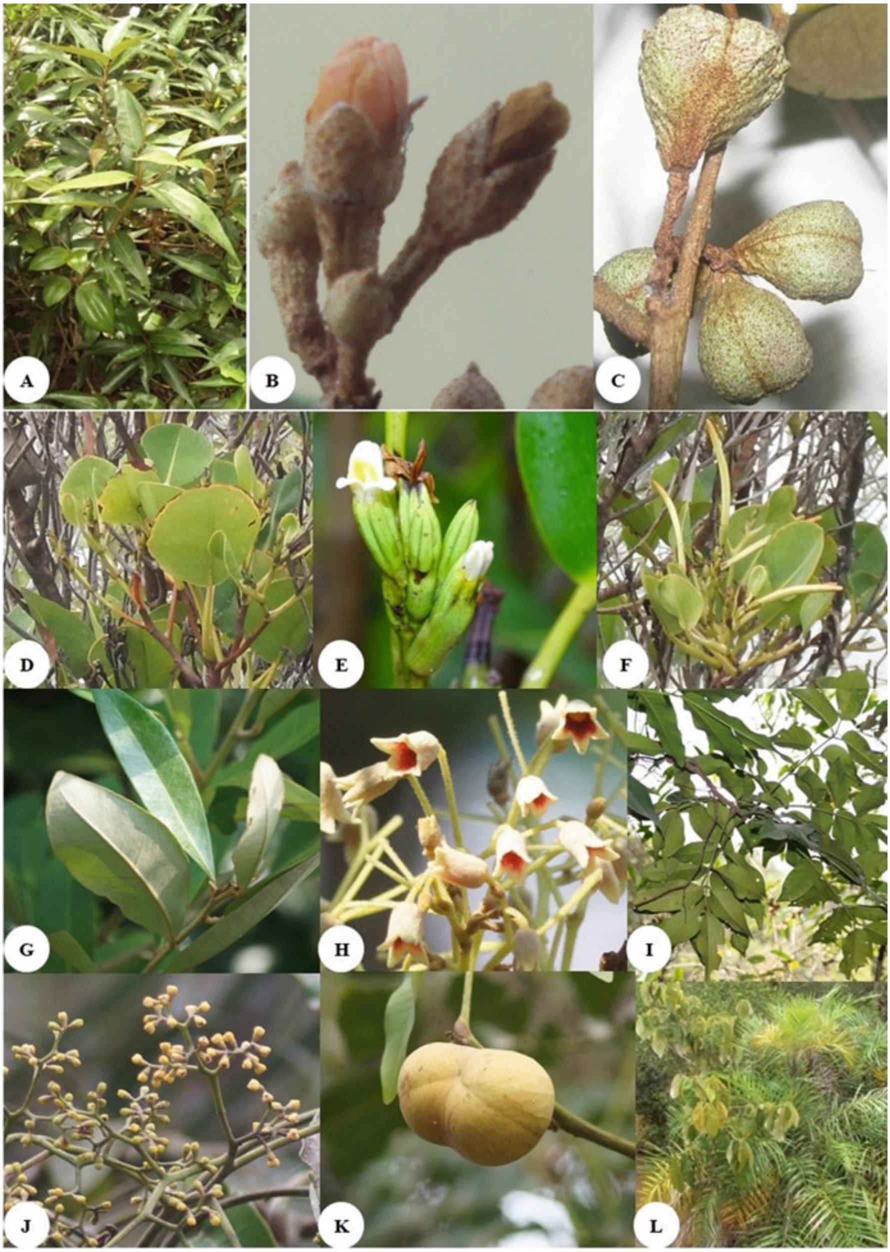

Fig. 8.3 Threatened true mangrove species of India. (**a**–**c**) *Brownlowia tersa*. (**d**–**f**) *Aegialitis rotundifolia*. (**g**–**h**) *Heritiera fomes*. (**i**–**k**) *Aglaia cucullata*. (**l**) *Phoenix paludosa*. (Images of *Heritiera fomes* and *Aglaia cucullata* courtesy of Mr. Muktipada Panda, Assistant Professor, Regional Institute of Education, Bhubaneswar, National Council of Educational Research and Training, Government of India)

by ecologists to evaluate the dimensions of the forest as an ecosystem (Pool et al. 1977; Kangas 2006). The forest structure of mangroves has been studied with respect to the functionality of restored/planted mangroves (Bosire et al. 2008; Brown et al. 2013; Laulikitnont 2014), faunal diversity (Cannicci et al. 2008), sedimentation (Furukawa and Wolanski 1996; Kathiresan 2003; Lovelock et al. 2005), litter-fall (Dagar 1993; Dagar and Sharma 1991, 1993; Dagar et al. 1991), biomass and carbon sequestration (Perera and Amarasinghe 2014; Kauffman and Bhomia 2017), habitat creation (Nagelkerken et al. 2008; Hendy et al. 2014), and shoreline protection (Bao 2011; Spalding et al. 2014).

In the Indian context, studies on mangrove forest structure are very limited. Forest structural studies on Indian mangrove forests at Pichavaram and Muthupet (Muniyandi 1986; Kathiresan et al. 1994, 2016), in the Andaman Islands (Dagar 1982, 1987, 1993, 1995, 1998, 2003, 2005, 2008; Singh et al. 1990; Mall et al. 1991; Dagar and Sharma 1989, 1991, 1993; Dagar et al. 1991, 1993; Dagar and Dagar 1986, 1991, 1999; Dagar and Singh 1999; Singh and Odaki 2004; Ragavan et al. 2015; Kiruba-Sankar et al. 2018), in Odisha (Mishra et al. 2004; Upadhyay and Mishra 2008, 2010), in Andhra Pradesh (Azariah et al. 1992; Venkanna and Narasimha Rao 1993; Satyanarayana et al. 2002, 2009), in Kerala (Nameer et al. 1992; Suresh Kumar and Mohan Kumar 1997; Rahees et al. 2014; Vijayan et al. 2015; Rani et al. 2016; George et al. 2017; Sreelakshmi et al. 2018), in Gujarat (Sawale and Thivakaran 2013), and in the Sundarbans (Mukherjee and Mukherjee 1970; Matilal et al. 1986; Chaudhuri and Chakrabarti 1989; Saha and Choudhury 1995; Joshi and Ghose 2003, 2014; Naskar and Mandal 1999) are noteworthy. The complexity index (I_c) and important value index (I_v) are structural indices that are often used to express the existence of stress in the forest stand and the importance of a tree species within a stand of mixed species, respectively. In general, high stem density, low species richness, low canopy height, and low basal area are indicative of the least complex stands (often in arid regions), whereas high canopy height, high basal area, and low stem density indicate complex stands (common in wet humid regions). On the basis of the available literature, it is evident that with the exception of the Andaman and Nicobar Islands, all mangrove habitats in India have low I_c values and *Avicennia* spp. constitute the important tree species, whereas mangrove habitats in the Andaman and Nicobar Islands exhibit a high I_c value and *Rhizophora* spp. constitute the important tree species (Table 8.3). The low I_c value indicates the low structural development and the prevalence of disturbances in these mangrove stands. Further abundance of *Avicennia* species indicates the prevalence of high-salinity conditions in Indian mangrove habitats. Thus, despite the high species richness, species with low salinity tolerance have restricted distribution. The abundances may decline long before the species richness does, and so species of low abundance should be given high conservation priority. Furthermore, monospecific stands may have low thresholds for perturbations and may thus be more vulnerable to environmental changes; for example, attack by diseases, drought, sedimentation, and flooding are among the stresses. Globally, as well as in India, most mangrove forest structural studies have been carried out to assess changes in the structure and functions of mangroves and to initiate proper conservation

Table 8.3 Results of mangrove forest inventory studies on Indian mangroves

State	Place	Density (ha^{-1})	Basal area (m^2 ha^{-1})	Complexity index	Dominant species	Reference
Kerala	Cochin	1000–3500	0.67–3.85	1.684–13.390	*Avicennia officinalis*	Rajagopalan (1992)
	Puduvyppu	355–1367	0.2–8.60	–	*Avicennia officinalis*	Nameer et al. (1992)
	Puduvyppu	3068	10.9	–	*Avicennia officinalis*	Suresh Kumar and Mohan Kumar (1997)
	Kadalundi Vallikkunnu community reserve	11,256	83.09	–	*Avicennia officinalis*	Rahees et al. (2014)
	Kollam	18,277	108.67	–	*Avicennia officinalis*	Vijayan et al. (2015)
	Cochin	7680–11,760	54.86–103.25	–	*Avicennia officinalis*	Rani et al. (2016)
	Entire Kerala	10–13,846	0.02–20.19	–	*Avicennia officinalis*	Sreelakshmi et al. (2018)
	Entire Kerala	250–2636	2.84–44.96	18.30–109.81	*Avicennia officinalis*	George et al. (2018)
West Bengal	Lothian Island, Sundarbans	912–7031	4.2–19.2	1.1–6.8	*Avicennia marina*	Joshi and Ghose (2003)
	Lothian Island, Sundarbans	912–7031	4.2–19.2	1.1–6.8	*Acanthus ilicifolius*, *Avicennia marina*	Joshi and Ghose (2002)
	Lothian Island, Sundarbans	4723–23,751	11.7–13.7	4.1–73.3	*Avicennia marina*, *Aegiceras corniculatum*, *Excoecaria agallocha*	Joshi and Ghose (2014)
	Sundarbans	1100–16,400	–	–	*Avicennia alba*, *Acanthus ilicifolius*	Matilal et al. (1986)
	Sagar Island	160.3–335.6/100 m^2	–	–	*Avicennia alba*, *Excoearia agallocha*	Saha and Choudhury (1995)

Andaman and Nicobar Islands	Andaman Islands	124–214	–	–	*Rhizophora apiculata*, *Rhizophora mucronata*	Mall et al. (1991)
	Andaman Islands	250–32,140	–	–	*Rhizophora mucronata*	Das et al. (2014)
	Andaman and Nicobar Islands	487–2383	–	–	*Rhizophora apiculata*	Ragavan et al. (2015)
	Andaman Islands	1252–2200	30.8–59.6	196.84–507.48	*Rhizophora apiculata*	Kiruba-Sankar et al. (2018)
Odisha	Bhitarkanika	7186–13,536	21.69–37.04	–	*Heritiera fomes*, *Excoecaria agallocha*	Mishra et al. (2005)
	Bhitarkanika	7450–17,943	–	–	*Heritiera fomes*, *Excoecaria agallocha*	Upadhyay and Mishra (2008)
	Bhitarkanika	2012–3586	3.17–7.55	–	*Excoecaria agallocha*, *Avicennia officinalis*, *Hertiera fomes*	Upadhyay and Mishra (2014)
Tamil Nadu	Pichavaram	1641	–	–		Kathiresan et al. (2016)
Andhra Pradesh	Coringa mangrove forest	6140	–	–	*Excoecaria agallocha*	Azariah et al. (1992)
	Krishna mangroves	734–5009	–	–	*Excoecaria agallocha*	Venkanna and Narasimha Rao (1993)
	Godavari mangroves	90–17,310	0.01–120	–	*Avicennia marina*	Satyanarayana et al. (2009)
		47 and 1731 stems/0.1 ha	0.1 and 10.9 m^2/ 0.01 ha		*Avicennia marina*	Satyanarayana et al. (2002)
Gujarat	Mundra coast and Kharo creek	1820–4325	–	–	*Avicennia marina*	Sawale and Thivakaran (2013)
	Gulf of Kachchh	350–1567			*Avicennia marina*	Thivakaran et al. (2018)
Maharashtra	Mumbai	325–708	5.60–28.26	0.06–4.56	*Avivennia marina*	Kantharajan et al. (2018)

measures prior to large-scale degradation. But, unfortunately, long-term monitoring of the forest structure of mangroves is inadequate and has resulted in ignorance of forest structural information in decision making.

Mangrove zonation—distribution of tree species in monospecific bands parallel to the shoreline—has been described as the classical feature of mangrove forests and was presumed to be present in all mangroves worldwide in the past (Chapman 1975; Snedaker 1982). The hypothesis provided for the occurrence of zonation in mangroves are plant succession due to land building, response to geomorphological factors, physiological adaptation to gradients across the intertidal zone, differential dispersal of propagules, differential predation on propagules across the intertidal zone, and interspecific completion (Smith 1992). However, not all researchers have supported this classical view of mangrove zonation (Thom 1967; Thom et al. 1975; West 1956; Macnae and Kalk 1962). Furthermore, exclusive studies on mangrove zonation in various regions of the globe (Bunt et al. 1991; Bunt 1996, 1999; Bunt and Bunt 1999; Bunt and Stieglitz 1999; Ellison et al. 2001; Schmiegelow and Gianesella 2014) have revealed lack of zonation (i.e., absence of strong relationships between species distribution and an edaphic gradient). Thus, a classical zonation pattern in mangrove forest tends to be an exception rather than the rule (Smith 1992). Zonation in Indian mangroves has also been described by many researchers (Sidhu 1963; Blasco 1977; Dagar 1982; Dagar et al. 1991; Dagar and Singh 1999) and has often been viewed as three conspicuous zones—proximal, middle, and distal zones, followed by a fourth littoral zone—solely on the basis of their generalized view on the distribution pattern of mangrove species. Thus, it has been suspected that many reports in the literature on species zonation in mangrove swamps do not accurately reflect the truly complex vegetation patterns found in mangrove forests. Rather, these reports rely on qualitative assessments of profile diagrams constructed with a priori assumptions of zonation (Ellison et al. 2001). Since different species of mangroves respond differently to underlying edaphic gradients, and many mangrove species can grow in a broad range of conditions found across the intertidal zone, understanding of the site-specific habitat suitability of mangrove species and the interconnection between various components of the mangrove ecosystem require elaborate study to underpin the true science behind mangrove zonation.

8.3.1 Genetic Diversity

The population structure and the distance over which gene flow occurs can inform management decisions regarding conservation and management of threatened ecosystems (Homer 2009). Since mangroves are at elevated risk, understanding of genetic status and the degree of divergence among populations is necessary for successful prevention of their extinction (Zhang et al. 2010; Zhao et al. 2012). Globally, efforts have been made in recent times to understand the phylogeography and population structure of many mangroves species, viz., *Avicennia* spp. (Li et al. 2016a), *Ceriops* spp. (Huang et al. 2008), *Lumnitzera* spp. (Su et al. 2006; Li et al.2016b; Su et al. 2007), *Rhizophora* spp. (Lo et al. 2014; Ng et al. 2015; Wee et al.

2015; Yan et al. 2016; Guo et al. 2016), *Sonneratia* spp. (Yang et al. 2015, 2016, 2017), *Bruguiera* spp. (Urashi et al. 2013; Ono 2016), and *Xylocarpus* spp. (Guo et al. 2017). It was previously assumed that mangroves are genetically undifferentiated throughout their range as a result of long-distance oceanic dispersal of their propagules (Duke et al. 1998a, b; Maguire et al. 2000). However, recent molecular studies have shown strong genetic differentiation between populations of many mangrove species and revealed the role of vicariance and Pleistocene sea level fluctuations in shaping the current distribution pattern of mangrove species. Strong genetic differentiation has been reported between the populations of Indo-Malesia and Australasia and between South China Sea and Indian Ocean populations within Indo-Malesia. Furthermore, the roles of ocean currents, geomorphology, the hydrology of the estuary, and water surface currents in shaping the population structure of mangrove species have also been revealed by molecular studies (Dodd et al. 2002; Orsini et al. 2013; Wee et al. 2014; Cerón-Souza et al. 2015). In all of the aforementioned studies, extensive sampling was undertaken in South East Asia and East Asia (as representatives of Indo-Malesia) and in Australasia; only a few samples were studied from East Africa, the Middle East, and South Asia.

Fossil and molecular evidence has revealed that marine biodiversity hot spots have occurred in different places over time (Renema et al. 2008). So, an understanding of population structure and the extent of gene flow in the mangroves of East Africa, the Middle East, and South Asia—particularly in Indian mangroves, as they have more species richness among these regions—is greatly needed to provide a clearer picture of the phylogeography and genetic structure of Indo-West Pacific (IWP) mangroves. But, apart from a few region-specific studies (Parani et al. 1997a, b; Lakshmi et al. 1997, 2000; Jugale et al. 2009; Pawar et al. 2013; Gurudeeban et al. 2013; Saddhe et al. 2016; Dasgupta et al. 2017), the population structure of Indian mangroves has not been studied much. Furthermore, recent studies have shown low genetic diversity in widespread mangrove species of the world (Guo et al. 2018). So, an understanding of the population structure of Indian mangroves is desired for better understanding of the current distribution pattern of mangrove species and conservation measures.

8.3.2 Floral Diversity of Mangrove Forests (Mangrove Associates)

Saenger et al. (1983) listed—along with 60 exclusive mangroves—23 nonexclusive (associate) mangrove species found commonly across the world. Of these associate species, eight are commonly distributed in the Western hemisphere and 18 in the Eastern hemisphere. Dagar (2003) listed 188 species of associates, including climbers, epiphytes, and semiparasites found in Indian mangroves. These are important because they contribute to the structure of mangrove forests. The important species are shown in Table 8.4. This type of vegetation occurs on sandy and gravelly seashores, mostly behind the mangroves or boarding them. Mostly, this vegetation is not subject to continuous immersion, and only the high tide reaches it, but it remain under a constant maritime influence all around the coast. The most characteristic

Table 8.4 Distribution of important species associated with mangroves

Species	Life-form	West coast	East coast	Andaman and Nicobar Islands
Aeluropus lagopoides	Grass	+	+	+
Aganope thyrsiflora	Straggling shrub	–	–	+
Allophyllus cobbe	Shrub	–	+	+
Amoora cocullata	Tree	–	+	+
Ardisia elliptica, *Ardisia solanacea*	Tree	–	+	+
Arthrocnemum indicum	Under shrub	+	–	–
Aryteria lottoralis	Tree	–	–	+
Atriplex stocksii	Under shrub	+	–	–
Azima tetracantha	Shrub	–	+	–
Barringtonia acutangula	Tree	+	+	+
Barringtonia racemosa	Tree	+	+	+
Caesalpinia crista	Struggling shrub	+	+	+
Caesalpinia nuga	Struggling shrub	+	+	+
Calophyllum inophyllum	Tree	+	+	+
Carallia brachiata	Tree	+	–	+
Cassytha filiformis	Trailer	–	+	+
Cayratia carnosa	Twiner	–	+	+
Cerbera manghas	Tree	+	+	+
Clerodendrum inerme	Shrub	+	+	+
Clitoria ternatea	Twiner	+	+	+
Crinum asiaticum	Under shrub	+	+	+
Crinum defixum	Under shrub	–	+	+
Colubrina asiatica	Shrub	+	+	+
Cordia subcordata	Tree	–	–	+
Cycas rumphii	Shrub	–	–	+
Dalbergia spinosa	Shrub	+	+	+
Dendrophthoe falcata	Semiparasite	–	+	+
Derris heterophylla	Climber	+	+	–
Derris scandens	Climber	–	+	–
Derris sinnuata	Climber	–	+	–
Derris trifoliata	Climber	+	+	+
Dischidia nummularia	Epiphyte	–	+	+
Drynaria quercifolia	Epiphytic fern	–	–	+
Erythrina variegata	Tree	–	–	+
Ficus retusa	Tree	–	–	+
Fimbristylis ferruginea, *littoralis*	Sedge	+	+	+
Finlaysonia obovata	Climber	–	+	+

(continued)

Table 8.4 (continued)

Species	Life-form	West coast	East coast	Andaman and Nicobar Islands
Flagellaria indica	Climber	–	+	+
Ganophyllum falcatum	Tree	–	–	+
Guettardia speciosa	Tree	–	–	+
Halophila beccari	Grass	+	+	–
Heliotropium curassavicum	Herb	+	+	–
Hernandia peltata	Tree	–	–	+
Hibiscus tiliaceous	Tree	+	+	+
Hibiscus tortussus	Tree	–	+	–
Hoya parasitica	Parasite	–	+	+
Hydnophytum fornicarum, andamanensis	Epiphytic shrub	–	–	+
Intsia bijuga	Tree	–	+	+
Ipomoea pes-caprae	Trailer	+	+	+
Ipomoea tuba	Climber	–	+	+
Launea sarmentosa	Herb	–	+	+
Licuala spinosa	Palm	–	–	+
Macaranga peltata	Tree	–	–	+
Macrosolen cochinchinensis	Parasite	–	+	–
Manilkara littoralis	Tree	–	+	+
Morinda citrifolia	Tree	–	–	+
Mucuna gigantea	Woody climber	+	+	+
Myriostachya wightiana	Grass	+	+	+
Ochrosia oppositifolia	Tree	–	–	+
Pandanus fascicularis	Tree	+	+	+
P. foetidus	Shrub	–	+	–
P. furcatus	Tree	+	+	–
P. tectoris	Shrub	–	+	–
Pongamia pinnata	Tree	+	+	+
Porteresia (Oryza) coarctata	Grass	+	+	–
Premna corymbosa	Shrub	+	+	+
Salacia chinensis	Climbing shrub	–	+	–
Salicornia brachiata	Herb	+	+	–
Salvadora oleoides	Tree	+	–	–
Salvadora persica	Tree	+	+	–
Sarcolobus carinatus, Sarcolobus globosus	Climber	–	+	+
Sarcolobus globosus	Climber	–	+	–
Scaevola taccada	Tree	–	–	+
Scirpus littoralis	Sedge	+	+	+
Scyphiphora hydrophyllacea	Tree	–	–	+
Semicarpus heterophylla	Tree	–	–	+

(continued)

Table 8.4 (continued)

Species	Life-form	West coast	East coast	Andaman and Nicobar Islands
Sesuvium potulacastrum	Trailer	+	+	–
Sophora tomentosa	Tree	–	–	+
Spinifex littoreus	Trailer	+	+	–
Stenochlaena polustrae	Climber	+	+	+
Stictocardia tiliifolia	Climber	+	+	+
Suaeda fruticosa	Herb	+	+	–
Suaeda maritima	Herb	+	+	–
Suaeda monoica	Herb	+	+	–
Suaeda nudiflora	Herb	–	+	–
Syzygium samarangensis	Tree	–	–	+
Tamarix gallica	Shrub	+	+	–
Tamarix troupii	Shrub	+	+	–
Terminalia catappa	Tree	+	+	+
Thespesia populnea	Tree	+	+	+
Thuarea involuta	Grass	+	–	+
Tournefortia ovata	Shrub	+	–	+
Triumfetta repens	Creeper	–	–	+
Tylophora tenuis	Climber	_	+	+
Urochondra setulosa	Grass	+	–	–
Vigna marina	Twiner	–	–	+
Viscum monoicum	Parasite	–	+	–
Viscum orientale	Parasite	–	+	–
Vitex negundo	Shrub	–	+	+
Wedelia biflora	Herb	–	+	+
Wrightia tomentosa	Tree	–	–	+
Ximenia americana	Tree	–	+	+
Zoysia matrella	Grass	+	+	+

Dagar (1982, 2003), following Saenger et al. (1983), included *Acrostichum aureum*, *Acrostichum speciosum*, *Agalaia cocullata*, *Brownlowia tersa*, and *Dolichandrone spathacea* among associated species that have now been included in mangroves. For details of distribution in various stands, please see Dagar et al. (1991, 1993); Dagar (2003) and Dagar and Singh (2007)

species of this formation are evergreen but very light-foliaged species, such as *Casuarina equisetifolia*, which often form a pure fringe (e.g., Casuarina Bay in the Andamans) or are found growing on a sandy substratum along the sea coast.

The most common of these species include *Aglaia cucullata*, *Arthrocnemum indicum*, *Atriplex stocksii*, *Barringtonia asiatica*, *B. racemosa*, *Brownlowia tersa*, *Caesalpinia crista*, *C. nuga*, *Calophyllum inophyllum*, *Cerbera manghas*, *Clerodendrum inerme*, *Dalbergia spinosa*, *Dendrophthoe falcata*, *Derris heterophylla*, *D. scandens*, *D. sinuata*, *D. trifoliata*, *Dolichandrone spathacea*, *Guettarda speciose*, *Hernandia peltata*, *Hibiscus tiliaceous*, *H. tortussus*, *Intsia bijuga*, *Licuala spinosa*, *Manilkara littoralis*, *Merope angulata*, *Ochrosia* *oppositifolia*, *Pandanus fascicularis*, *P. foetidus*, *P. furcatus*, *P. tectoris*, *Pongamia pinnata*, *Premna corymbosa*, *Salvadora persica* (on the west coast only), *Scaevola taccada*, *Terminalia catappa*, *Thespesia populnea*, *Tournefortia ovata*, and *Vitex negundo*. Some species are distributed in restricted habitats. For example, *Arthrocnemum indicum* and *Salvadora persica* are found along the Gujarat coast in pure patches, while *Cycas rumphii* (a gymnosperm) is common along the Nicobar coast and *Licuala spinosa* is a common palm in the Andamans. Climbers such as *Finlaysonia obovata*, *Flagellaria indica*, *Mucuna gigantea*, *Salacia chinensis*, *Sarcolobus*, *S. globosus*, *Stictocardia tiliifolia*, *Stenochlaena palustrae*, *Tournefortia ovata*, and *Tylophora tenuis* are quite frequent. *Dischidia nummularia* and *Hoya parasitica* are found hanging on branches very frequently. *Viscum monoicum* and *Viscum orientale* are common parasites. *Cassytha filiformis*, *Ipomoea pes-caprae*, *I. tuba*, *Sesuvium portulacastrum*, and *Spinifex littoreus* are common trailers on sandy beaches. These are mixed with herbaceous species such as *Aeluropus lagopoides*, *Fimbristylis ferruginea*, *Halophila beccari*, *Heliotropium curassavicum*, *Launea sarmentosa*, *Myriostachya wightiana*, *Porteresia (Oryza) coarctata* (a dominant grass in the Sundarbans), *Salicornia brachiata*, *Scirpus littoralis* (a common sedge in stagnant water), *Suaeda fruticosa*, *S. maritima*, *S. monoica*, *S. nudiflora*, *Thuarea involuta*, *Urochondra setulosa* (a common grass along the Gujarat coast), *Wedelia biflora*, and *Zoysia matrella.*

8.3.3 Faunal Diversity

In recent times it has been understood that mangrove-associated fauna play a significant role in shaping the mangrove forest structure and the functioning of the ecosystem (Kristensen 2007; Lee 2007; Cannicci et al. 2008; Kristensen et al. 2008; Nagelkerken et al. 2008). Sediments, root structures, and large woody debris are the three main substrata that fauna can exploit in mangroves (Kristensen 2007; Ellison and Farnsworth 1990; Ellison et al. 1996; Cragg and Hendy 2010; Hendy et al. 2013). The faunal communities in mangroves chiefly consist of terrestrial animals (insects, birds, mammals, and reptiles), aquatic animals (fish, crustaceans, mollusks, and echinoderms), and benthic animals (polychaetes, brachyuran crabs, wood-boring animals, mud-burrowing bivalves, gobiid fish, and gastropods) and some sessile bivalves, such as oysters, *Modiolus* spp., and barnacle crustaceans (Kathiresan et al. 2015). In the Sundarbans, even the tiger is part of this association, and in the Andaman and Nicobar Islands, the tribal people (mainly the Onge, Jarawas, Sentinelese, Great Andamanese, Shompen, and Nicobarese) are dependent mainly on these resources (Dagar and Dagar 1986, 1991, 1999; Dagar and Singh 1999). However, the faunal assemblages in mangroves are significantly less studied and documented than the forests they inhabit. As per the available estimates, the mangrove forests of India support diverse groups of fauna comprising 3182 species (Kathiresan 2018; Table 8.5). This is perhaps the largest biodiversity record in world mangrove ecosystems (Kathiresan 2000). There are greater numbers of invertebrate species than vertebrate species. The numbers of faunal species so far recorded are

Table 8.5 Faunal and microbial diversity of Indian mangroves

Group		Number of species
Faunal diversity	Prawns and lobsters	55
	Crabs	145
	Insects	661
	Mollusks	337
	Other invertebrates	745
	Fish parasites	7
	Finned fish	554
	Amphibians	13
	Reptiles	84
	Birds	513
	Mammals	68
	Total faunal diversity	*3182*
Microbial diversity	Bacteria	69
	Fungi	103
	Actinomycetes	23
	Lichens	32
	Total microbial diversity	*227*

Source: Kathiresan (2018)

highest (2061) in the mangroves of the east coast, followed by 922 species in the Andaman and Nicobar Islands and 727 species on the west coast (Kathiresan et al. 2015). In recent times there has been an active research community focusing on documentation of faunal diversity at different sites of Indian mangroves (Gopikumar et al. 2008; Khaleel 2008; Bhosale 2008; Remadevi et al. 2008; Latheef et al. 2008; Rajavel and Natarajan 2008; Santhakumaran 2008; Sahoo and Ansari 2017, Sahoo et al. 2018). However, the knowledge on the faunal assemblage and its role in the ecosystem sustainability of Indian mangroves is far from complete. Most of the faunal studies on Indian mangroves have been mostly focused on description and distribution, but their roles in shaping the forest structure and ecosystem functioning have not been determined, because of a lack of consistency in quantitative data (Sunil Kumar 2000; Kathiresan et al. 2015). Furthermore, with the exceptions of the Sundarbans of West Bengal, Pichavaram in Tamil Nadu, Goa, and Cochin in Kerala, all mangrove habitats have been little explored with respect to faunal diversity.

8.3.4 Microbial Diversity

Mangroves harbor diverse groups of microorganisms, and all microbial forms—including bacteria, fungi, cyanobacteria, microalgae, macroalgae, and fungus-like protists—have been reported in this ecosystem. Diverse microbial communities residing in mangroves perform an important role in nutrient cycling and regulate the chemical environment of the ecosystem (Alongi et al. 1993; Holguin et al. 1999;

Kathiresan and Bingham 2001). In particular, microbial activity is the sole process of nutrient transformation within the nutrient-poor mangrove ecosystem (Alongi et al. 1993; Holguin et al. 1999). In tropical mangroves, bacteria and fungi constitute 91% of the total microbial biomass, whereas algae and protozoa represent only 7% and 2% of it (Alongi 1988). Despite the very rich microbial diversity in mangroves, fewer than 5% of species have been described; in many cases, neither their ecological role nor their application potential is known. Among different groups of microorganisms, bacteria (nitrogen fixers, phosphate solubilizers, cellulose decomposers, nitrifiers and denitrifiers, sulfur oxidizers, iron oxidizers, methanogens, and iron reducers) are important participants in the carbon, sulfur, nitrogen, and phosphorus cycles in mangrove ecosystems (Alongi 1994; Holguin et al. 2001; Rojas et al. 2001). The physicochemical characteristics of the soil influence microbial activities in mangroves to a great extent, resulting in changes in key biogeochemical cycles (Gutknecht et al. 2006). Soil biochemical and microbial characteristics are important indicators of the vegetation of mangroves (Dinesh and Chaudhuri 2013); further, it has been reported that plant–soil–microbe interactions contribute to the spatial patterning of vegetation and soil variables across the intertidal zones of many mangrove forest communities (Sherman et al. 1998). So, an understanding of plant–soil–microbe interactions is essential. Besides their ecological role, microorganisms in mangrove environments are a major source of antimicrobial agents and also produce a wide range of important medicinal compounds, including enzymes, antitumor agents, insecticides, vitamins, immunosuppressants, and immune modulators.

Despite global advancement in the understanding of microbial diversity and the roles of microbes in different mangrove environments, little is known about their diversity and roles in Indian mangroves, and the scientific basis of the biogeochemical cycles of the habitat is not yet understood. Further, most studies have been of a descriptive nature, designed for taxonomic and inventory interests (Sunil Kumar 2000), and observations relating microbes to ecosystem-level processes in Indian mangroves are rare. As per recent estimates, there are 69 species of bacteria, 103 species of fungi, 23 species of actinomycetes, and 32 species of lichens known from Indian mangroves (Kathiresan 2018; Table 8.5). In recent times, a few attempts have been made to provide a comprehensive account of microbial diversity and distribution in the Sundarbans (Ramanathan et al. 2008; Das et al. 2012), Bhitarkanika (Mishra et al. 2012), the Gulf of Kachchh (Goutam and Ramanathan 2013), and Pichavaram (Saravanakumar et al. 2016, 2018), with an aim to improve our understanding of bacterial functionality and microbial interactions found in those ecosystems. However, the microbial diversity of other mangrove habitats in India remains unexplored. It is critically important to understand the microbial ecology of the mangrove sediments in the present context of global warming and sea level rise, besides man-made threats to ecologically sensitive mangrove habitats (Gilman et al. 2008). The immense phenotypical and genetic diversity of soil bacteria and fungi make such studies very difficult. However, recent developments in molecular techniques, such as metagenomics, will help to explore a good percentage of the microbial community that can be exploited for the welfare of mankind, as well for better understanding of mangrove ecosystem functioning. Since microbes play key roles in productivity, plant fitness, survival, and overall ecosystem resilience, information on the diversity and structure of microbial communities in mangrove environments and their roles in ecosystem functioning is imperative for better conservation and management of mangroves (Bashan and Holguin 2002). Kathiresan has contributed a full-length chapter to this volume on the roles of microbes associated with mangroves.

8.3.5 Productivity

Mangrove swamps, being very productive areas, provide the base of the food chain in the nearby sea and coastal waters, and serve as a link between the terrestrial and marine ecosystems. Nutrients received from the trees, litter-fall, and dissolved organic matter go into the sea and are consumed by the resident fauna. Floral elements, phytoplankton, and seaweeds are the primary sources of primary productivity, and zooplankton and benthic animals are the secondary and tertiary producers, respectively. A variety of animals depend partially or wholly on the mangrove ecosystems. Many species of wildlife, such as turtles, visit sandy shores near mangroves to lay eggs. The food web of the mangrove ecosystem is very complex and interesting. The rough estimate of total mangrove net primary production (NPP) is 209.6 Tg C year^{-1} (Alongi and Mukhopadhyay 2015). Of which, ~20% (34.1 Tg C year^{-1}) of the carbon is lost or recycled via CO flux to the atmosphere and ~60% (117.9 Tg C year^{-1}) are exported as particulate organic carbon (POC), dissolved organic carbon (DOC), and dissolved jnorganic carbon (DIC) to the ocean (Alongi and Mukhopadhyay 2015; Rosentreter et al. 2018). Of the remaining carbon, burial accounts for between 18.4 and 34.4 Tg C year^{-1} (Breithaupt et al. 2012), and this blue carbon is considered a significant long-term storage of atmospheric CO2 (Rosentreter et al. 2018). However, there is no robust estimate for carbon stock of global mangroves. As per a recent estimate, carbon sequestration in the mangroves amounts to 14.2 Tg C year^{-1} with an average sequestration rate of 171 ± 17.1 g C m^{-2} year^{-1} with an average soil accretion rate of 5.8 mm year^{-1} (Alongi 2018). In recent times, efforts have been taken to assess the carbon stock of global mangroves; however, uncertainty still exists. For instance, the available estimates of total global carbon stock of mangroves are 4.03 PgC (Twilley et al. 1992), 20 PgC (Donato et al. 2011), 13.1 PgC (Alongi 2014), 11.2 PgC (Sanders et al. 2016), 4.4 PgC (Atwood et al. 2017), and 10 PgC (Alongi 2018). The estimated mean mangrove carbon stocks per unit area were 511 Mg C ha^{-1} (IPCC 2013), 956 Mg C ha^{-1} (Alongi 2012; 2014), 885 Mg C ha^{-1} (Kauffman et al. 2017), and 761.4 ± 45.5 Mg C ha^{-1} (Alongi 2018), which are higher than that of the other forest ecosystems. Unlike other tropical forests, for which the bulk of carbon storage is in biomass, mangrove carbon is primarily stored in the soil (Donato et al. 2011; Murdiyarso et al. 2015; Sanders et al., 2016). The estimated average soil carbon concentration of global mangrove is also highly variable. For instance, Jardine and Siikamäki (2014) reported the global mangrove soil carbon stock as 5.00 ± 0.94 Pg C, whereas

Atwood et al. (2017) and Sanderman et al. (2018) have reported the mangrove soil carbon stock as 2.6 Pg C and 6.4 Pg C for the top meter of soil, respectively. Similarly, estimates of soil carbon stock per unit area also vary. Donato et al. (2011) reported the average mangrove soil organic carbon of 864 Mg C ha^{-1}, whereas Alongi (2014), Jardine and Siikamäki (2014), Atwood et al. (2017), and Sanderman et al. (2018) have reported the average soil carbon stock ~700 Mg C ha^{-1}, 369 ± 6.8 Mg C ha^{-1} (range 272–703 Mg C ha^{-1}), 283 ± 193 Mg C ha^{-1} (72–936 Mg C ha^{-1}), and 361 ± 136 Mg C ha^{-1} (86–729 Mg C ha^{-1}), respectively. Despite the discrepancy in the estimates, certainly soil carbon stock per unit area of mangrove forest was highest than the other forest ecosystem in all the studies. However, the restricted global distribution and severe lack of countrywide data warrant the role of mangroves in climate change mitigation most effective at national level than the global scale (Taillardat et al. 2018). So, it is crucial to estimate and understand the spatial distribution of mangrove soil carbon stocks of all mangrove nations to recognize the actual climate mitigation potential of this ecosystem as well as to strength conservation measures.

Biomass and carbon squestration studies in mangroves forests of india are limited. The primary productivity of mangrove water ranges from 0.2 to 0.5 g C m^2 day^{-1} at Ariel Bay, Mayabunder, and Rangat; from 0.5 to 1.0 g C m^2 day^{-1} at Chiriatapu, Wandoor, and Nancowry; and from 2.0 to 3.6 g C m^2 day^{-1} in mangroves adjacent to mud flats and creeks in Phoenix Bay (Nair and Gopinathan 1983; Rajgopalan 1987). Major inorganic elements in the leaves of mangroves vary in different species (Dagar and Singh 1999), and the sodium-to-potassium ratio is much lower (from 0.67 in *Pongamia pinnata* to 11.47 in *Bruguiera gymnorrhiza*) than in seawater (38.5). Balachandra (1988) reported the yield of wood in various groups of islands. The average yields in the North, Middle, and South Andamans were found to be 115, 105, and 59 m^3 ha^{-1}, respectively. The standing biomass values of two natural stands of mangrove forests—one dominated by species of *Rhizophora* only and the other having a mixed association of species of *Bruguiera*, *Lumnitzera*, *Avicennia*, *Rhizophora*, *Sonneratia*, and *Xylocarpus*—were found to be 124 and 214 Mg ha^{-1}, respectively (Mall et al. 1991).

The estimated total biomass in mangrove forests in India is 41.2 million tonnes, of which 32.7 million Mg is aboveground biomass and 8.5 million Mg is belowground biomass (Suresh et al. 2017). The total C stocks in Indian mangrove forests are 20.59 million Mg. West Bengal, Gujarat, and the Andaman and Nicobar Islands account for more than 80% of the C stocks of Indian mangrove forests. Mangroves in India have the potential to sequester 0.218 million Mg C $year^{-1}$ (Suresh et al. 2017). As per recent estimates, global mangrove soils contain 369 ± 6.8 Mg C ha^{-1}, on average, in the top meter; most carbon-rich mangroves contains 703 ± 38 Mg C ha^{-1}, whereas the world's most carbon-poor mangroves contain 272 ± 49 Mg C ha^{-1}. Globally, mangrove soils contain 5.00 ± 0.94 Pg C. Indian mangroves contain 0.13 Pg C, which represents 2.6% of the global total (Jardine and Siikamäki 2014).

8.4 Physicochemical Characteristics of the Soil

The physicochemical properties of the soil have direct impacts on the structure and function of mangrove ecosystems, providing essential nutrients for growth and the physical structure for anchorage and stability (Boto and Wellington 1984). Salinity, iron sulfide concentrations, soil redox potential, nutrient content, organic matter, and physiographical position are important soil attributes determining the biodiversity and functioning of mangroves (Sherman et al. 1998; Marchand et al. 2004; Otero et al. 2006, 2009). Of these, salinity, nutrient content, and soil texture play the most significant roles (Ukpong 1997). A recent comprehensive description of mangrove soil revealed the occurrences of large differences between mangrove forests with respect to various soil attributes, influencing the ecophysiology, vegetation, species composition, and forest structure of mangroves (Hossain and Nuruddin 2016). On the basis of the available literature, it is evident that spatial differences in salinity and pH influence the species composition and distribution of the mangrove forest, whereas the forest structure of mangroves is influenced by salinity, soil moisture content, soil temperature, soil erosion, the sedimentation rate, and nutrient input (Joshi and Ghose 2003; McDonald et al. 2003; Perera et al. 2013), of which the content and availability of nutrients play the most significant roles in the structure and productivity of mangroves (Reef et al. 2010). Two major elements (N and P) are of great significance for the growth of mangroves. In addition, microbial and benthic faunal assemblages in mangroves are influenced by soil attributes (Alongi 2009), and soil characteristics can be used as an indicator for assessing restoration trajectories in restored mangroves (Salmo et al. 2013).

In India, studies on the soil characteristics of mangroves in the Sundarbans (Sah et al. 1985, 1989; Bandopadhya 1986; Chattopadhyay et al. 1986; Matilal et al. 1986; Sarkar et al. 1991; Saha and Choudhury 1995; Pal et al. 1996; Joshi and Ghose 2002, 2003, 2014; Dural et al. 2011), in Odisha (Banerjee and Rao 1990; Sahu et al. 2013; Sahoo et al. 2017), in Pichavaram (Ramanathan 1997; Ramanathan et al. 1999; Kathiresan et al. 1996), and in the Andaman and Nicobar Islands (Singh and Mongia 1985; Singh et al. 1989; Mongia and Ganeshamurthy 1989; Dagar et al. 1991, 1993; Mongia et al. 1993; Dagar and Singh 2007; Chaudhuri et al. 2009) are noteworthy. However, only a few studies have discussed the influences of soil characteristics on species composition and forest structure. Further, the information on other mangrove habitats of India is scanty. Although the strong correlations between mangrove species distribution and spatial variation in soil physiochemical parameters suggest that interactions between the biotic and abiotic environment exist, the direction of the interaction is not clear. So, understanding of site-specific soil characteristics is invaluable to underpin the interconnection between various components of the mangrove ecosystem and adjoining coastal ecosystems.

8.5 Economic Valuation of Ecological Services

Economic valuation of ecological services offered by an ecosystem is a precise tool for conservation policy decisions and governance (Costanza et al. 2014). The ecological services offered by mangroves are well known and have high significance for human well-being (Kumar 2010). The goods and services that mangrove forests offer globally have been valued at up to USD 194,000 ha^{-1} $year^{-1}$ (Costanza et al. 2014), and in Southeast Asia these ecosystem service benefits have been valued at an average of USD 4200 ha^{-1} $year^{-1}$ (Brander et al. 2012). However, global economic valuations of coastal forests, such as mangrove ecosystems, is rather limited, and the valuation methods, data, and classification systems used for ecosystems have been developed primarily for terrestrial ecosystems (Liquete et al. 2013; Barbier 2011). There have been attempts at economic valuation of wetland ecosystems in general (Costanza et al. 1997; Barbier 1997; Binilkumar 2010), and mangroves in particular (Lal 2003; Sathirathai 2003; Gunawardena and Rowan 2005), in different parts of the globe. A variety of valuation methods have been used to value mangrove ecosystems and their services in a wide range of geographic regions. Market price method is the most common method for services that are paid for directly (i.e., food, raw material, carbon sequestration, recreation, and tourism), while benefit transfer (also referred to in the literature as "value transfer") is heavily used to value all other ecosystem services, except for air quality regulation, in mangroves as well as other blue carbon ecosystem service valuation studies (Himes-Cornell et al. 2018a, b). The mangrove valuation literature is not yet robust as most published studies focus on a small selection of ecosystem services based on the availability of benefit transfer values and the ability to easily measure values with market prices (Himes-Cornell et al. 2018b). Further, many ecosystem services that cannot be valued monetarily as they lie in the "grey market" (i.e., may not have a direct market price), but that are often equally important to local communities, are ignored (Mukherjee et al. 2014; Himes-Cornell et al. 2018b). Thus, despite providing wide range of ecosystem services, food, raw materials, moderating extreme events, erosion prevention and maintaining the life cycles of migratory species receive the bulk of the attention in the mangrove valuation literature, while cultural ecosystem services (CES) of mangroves remains least valued, particularly services like ornamental resources, pollination, and inspiration for culture, art, and design are never valued for mangroves in any region (Himes-Cornell et al. 2018b). To date, only three large-scale economic assessments specifically targeted toward mangrove ecosystems (Salem and Mercer 2012; Brander et al. 2012; Vo et al. 2012) have been done. However, intact mangrove forests are often undervalued due to the difficulty in estimating the value of the nonmarket ecosystem services. Further, the values of mangrove ecosystem services are highly variable across study sites due to the biophysical characteristics of the site, the socioeconomic characteristics of the beneficiaries of ecosystem services, and the valuation methods used (Brander et al. 2012; Himes-Cornell et al. 2018b).

Studies on valuation of the ecosystem services of Indian mangroves are very limited. Anneboina and Kumar (2012) assessed the role of mangroves in increasing marine fish output in India and reported that the marginal effect of mangroves on the total marine fish output was 1.86 Mg ha^{-1} $year^{-1}$ in 2011, which translated into a percentage contribution of mangroves to India's commercial marine fisheries output of 23%. Hussain and Badola (2010) quantified the value of provisioning services in terms of forestry and fishery products in Bitharkanika mangroves. The findings revealed that 14.2% of the fuel needs of each household was being met by the mangrove forests, and in offshore fishery the number of species caught and the income from the catch were higher in areas with mangroves (USD 44.61 h^{-1}) than in those without mangroves (USD 2.62 h^{-1}). The market price of the forestry and fishery products used by the people was estimated to be USD 107 $household^{-1}$ $annum^{-1}$. The resources extracted from mangrove forests contributed to more than 14.5% of the total income of each household. Chand et al. (2013) estimated that the total economic value of the Andaman mangroves was more than INR 125 million per year. The value of goods and services harvested per household per year was more than INR 61,000, and the value of mangroves per hectare in the Andaman and Nicobar Islands was more than INR 0.2 million.

Across all regions, the fisheries value of mangroves tends to be highest, followed by the fuelwood and coastal protection values. Since 2010, carbon sequestration and greenhouse gas regulation have emerged as services of interest because of the growing emphasis on "blue carbon" from coastal and marine ecosystems. Globally, the average economic value of carbon sequestration by mangroves is USD 967 ha^{-1} $year^{-1}$ (Salem and Mercer 2012). There can be significant variability in soil carbon stocks across different mangrove forests and even within the same mangrove forest (Adame et al. 2015; Kauffman et al. 2011). Understanding of the distribution of soil carbon in mangrove forests will be very important in prioritizing protection and restoration efforts for climate change mitigation (Sanderman et al. 2018). Besides the aforementioned services, economic valuation studies on other services, especially biodiversity, are few in India, as well as worldwide. Without a better global distribution of mangrove valuation studies, estimates of the natural capital value of mangrove stocks cannot be made accurately and precisely for many places. To identify and value the absolute economic value (monetary value) of the mangroves, a multidisciplinary approach is highly imperative as argued by Martín-López et al. (2014) and Himes-Cornell et al. (2018b).

8.6 Conservation Efforts

DasGupta and Saw (2013) reviewed the managerial aspects of Indian mangroves and highlighted the transition of Indian forest policies and their impacts on these extensive coastal ecosystems. In brief, as a signatory member of international conventions—namely, the Ramsar Convention (1971), followed by the Convention Concerning the Protection of the World Cultural and Natural Heritage (1972)—India formulated a comprehensive management plan to conserve mangroves. A National Mangrove Committee (NMC) was formed in 1976, as an first step, to advise on conservation measures and form a framework for effective implementation after the signing of the conventions. On the basis of the recommendation of this committee, 15 sites were selected for conservation of mangrove habitats during 1987. Apart from this, Indian mangrove habitats are legally protected under the Indian Forest Act of 1927, various state forest acts, the Forest (Conservation) Act of 1980, the Wildlife (Protection) Act of 1972, the Coastal Regulation Zone (CRZ) Notification (2011) under the Environmental Protection Act of 1986, the Environmental Impact Assessment Notification (EIA) of 1994, and the Coastal Aquaculture Authority Act of 2005.

Recognizing the degrading conditions of the mangroves, the governments have collaborated with national and international nongovernmental organizations (NGOs) to undertake rehabilitation programs in many places. In particular, since 1996, the M.S. Swaminathan Research Foundation (MSSRF; based in Chennai), in collaboration with the Ministry of Environment and Forests and the State Forest Department, has become actively involved in a mangrove rehabilitation program with local community participation. Consequently, the entire coastal area has been divided into two categories: a high-tidal-amplitude area (Gujarat and West Bengal) and a low-tidal-amplitude area (Mathew et al. 2010). In high-amplitude areas, the existing planting technique of direct seed sowing and planting of seedlings in mud flats has been followed, whereas in low-amplitude areas (in Tamil Nadu and Andhra Pradesh), canal bank planting has been used. This approach has been successfully demonstrated in mangrove forests at Pichavaram, Tamil Nadu, by the MSSRF (MSSRF 2002). The technique was first attempted in 1987 in mangrove forests at Muthupet, Tamil Nadu, and different models have since been developed (Baruah 2004). A “fish bone” design has been the most successful of all canal bank planting designs tried so far, and it happens to be the latest improved design for canal bank planting.

From 2002 to 2006, 41.95 km^2 of mangrove areas in Southern India were restored (Sahu et al. 2015; Bhatt and Kathiresan 2011). The largest area of mangroves restored is in Andhra Pradesh (19.78 km^2 since 1987), mostly in the East Godavari and Krishna districts. In Tamil Nadu, about 8.40 km^2 of mangroves (3.45 km^2 at Pichavaram, 2.95 km^2 at Muthupet, and 2 km^2 at Ramanathapuram) has been restored through plantation, and more than 52 km^2 is still available for mangrove restoration (Bhatt and Kathiresan 2011). In Kerala, 1.34 km^2 of mangroves in the Kannur Division have been restored since 1997. In Karnataka, the total mangrove area restored since 2000 is 12.44 km^2. In Gujarat, 384.08 km^2 of mangrove plantations were established during 2001–2009 by the Gujarat Forest Department. In addition, the Gujarat Ecology Commission, Gandhinagar, increased mangrove plantations to an extent of 55.46 km^2 during 2001–2007 by involving local communities (Pandey and Pandey 2011). Most of the mangrove restoration programs in India have been intended to increase the area of coverage, and most afforestation efforts have used *Avicennia* species, with a mixed survival rate. For instance, Sanyal et al. (1998) reported that between 1989 and 1995, 9050 ha of mangroves was planted in West Bengal but with only a 1.52% success rate, whereas the survival rates have been high in Andhra Pradesh (55–93%), Tamil Nadu (80–100%), Karnataka (45–95%), and Kerala (52–85%).

Despite the success of many rehabilitation efforts in India in terms of mangrove coverage, the functionality of the restored/afforested areas has not been assessed in terms of ecosystem function. Further, no efforts have been made to increase the populations of species at elevated extinction risk (*Sonneratia griffithii*, *Heritiera fomes*), and existing mangrove habitats have also experienced degradation due to environmental pollution, especially discharge of heavy metals and organic waste, and a reduced freshwater supply (Das Gupta and Shaw 2013). So, conservation measures require additional efforts to enhance the ecological health of Indian mangroves rather than increasing mangrove coverage alone.

8.7 Ecosystem-based Management of Mangroves: A Future Need

India, on a regional basis, is often referred to as a good example of conservation and restoration of mangrove ecosystems (Bhatt and Kathiresan 2012). This is solely based on the trend toward increased mangrove coverage, reported by the Forest Survey of India, using remote sensing studies. Despite the hike in coverage, the ecological health of Indian mangroves remains threatened by environmental pollution generated from upstream anthropogenic activities, rising salinity levels, and drastic reductions of freshwater flow. Recent study results also show that environmental pollution, especially discharge of heavy metals and organic waste, remains one of the most decisive factors for the overall ecological health of mangroves across almost all of India (Bhattacharya et al. 2003; Agoramoorthy et al. 2007; Remani et al. 2010; Bala Krishna Prasad 2012). Thus, with the exceptions of *Avicennia marina* and *Excoecaria agallocha*, all mangrove species are at varying degrees of threat, and most mangrove habitats, apart from the Andaman and Nicobar Islands, exhibit low structural development in India. Since mangrove plant species are the “keystone species” of mangrove ecosystems, the prevalence of low structural development and the elevated threat of species extinction show the low sustainability of Indian mangroves.

Ensuring the sustainability of an ecosystem by preserving biological diversity, ecological integrity, and ecological heath is the fundamental priority for conservation efforts. Thus, the approach to address the issue of nature conservation has changed from species to ecosystems, and recent efforts have been focused on an ecosystem-based management (EBM) approach (Mace 2014). However, mangrove conservation measures have not changed much, despite greater understanding of their valuable and irreversible ecological and economic benefits. Early conservation measures relied on creation of protected areas at undisturbed sites, and this remains a dominant ideology for many people today. Broadly, there are three recommended activities to improve mangrove management: more acquisition of private land that includes mangroves, better legal protections for mangroves, and expanded mangrove rehabilitation projects. Recently, Lewis et al. (2016) proposed a fourth parallel approach—early detection and pre-emptive rehabilitation—to prevent complete loss of plant structure and ecological function by long-term monitoring of changes in the hydrological and ecological status of mangroves.

In India, mangrove conservation measures have often relied on legal protection for existing mangroves and rehabilitation of degraded mangroves by monospecific plantation. Though a few rehabilitation efforts in India have been noted as successful on the basis of area coverage increases, their ecological status has not been monitored properly. Furthermore, no long-term monitoring efforts have been made to assess changes in the structure and function of Indian mangrove habitats. Since gradual decreases and eventual loss of mangroves, due to small-scale disturbances, pose a major threat to mangroves globally (Lewis et al. 2016), an effective, long-term, integrated, ecosystem-based protection, management, and rehabilitation strategy is crucial.

Ecosystem-based management (EBM) has been a highly topical issue in recent years, and several developed countries are moving toward this approach. However, EMB lacks a universal implementation framework because of a lack of consensus on the definition of EBM in the published literature and on the specific components comprising this approach (Morishita 2008). Furthermore, comprehensive EBM requires taking into account all interactions in an ecosystem, so a solid scientific understanding of ecosystem structure, processes, functions, and interactions (Borges et al. 2017) is invaluable. Furthermore, EMB recognizes humans and their cultural diversity as integral components of many ecosystems, maximizing ecosystem services while promoting ecological resilience and appropriate productive activities (Lithgow et al. 2017). So, apart from the existing conservation measures—which need to be continued, expanded, and improved—effective implementation of an ecosystem approach is essential for mangrove management. To do that, comprehensive knowledge of various components of mangrove ecosystems should be studied and integrated into policy making. Recently, Borges et al. (2017), for the first time, outlined an approach for systematic planning and EBM of mangroves, using Brazil as a study case, to tackle the apparent paradox of reconciling mangrove conservation and sustainable use. They emphasized the integration of social–ecological data, anthropogenic threats, and regional peculiarities in policy making to enhance the sustainability of mangroves.

Concerted mangrove research over the last several decades has revealed that the frequency and duration of tidal inundation are key factors that control all components of mangrove ecosystems. Since regional geomorphology influences the frequency and duration of tidal inundation, mangrove habitats on the same coastlines differ in terms of their biological diversity, structure, and function. Furthermore, recent genetic studies have also demonstrated high genetic differentiation among mangrove populations and low genetic diversity of widespread mangroves, which indicate lack of gene flow between populations (Guo et al. 2018). Similarly, the mangrove dependence of local communities and the ecological services offered by mangroves are also site dependent. For instance, Lee et al. (2014) pointed out that effective coastal protection provided by mangroves depends on factors at landscape/geomorphic to community scales and local/species scales. Similarly, Twilley et al. (2018) reported the influences of coastal morphology on variations in carbon sequestration in mangrove habitats. So, it is essential to categorize mangrove habitats on the basis of their social–ecological features, geological traits, genetic differentiation, and expected responses to climate change, and to formulate EBM by integrating various components of mangrove ecosystems to enhance the sustainability of mangroves.

8.8 Conclusion

On the whole, in India, mangroves seem to be extensively studied, but various components still remain inadequately understood. Mangrove coverage has experienced a trend toward an increase, and the number of mangrove taxa has also increased slightly according to documentation since the mid-1980s, but the populations and ecological status of mangrove habitats have not been tracked along the same trajectory. In the past, conservation programs for mangroves have largely been conducted with a lack of comprehensive species-specific information and have often been aimed simply at increasing the area of mangrove coverage. In terms of mangrove conservation, mangrove areas have been rehabilitated, but their ecological and economical services could not be fully restored. Since mangroves are present in the land–sea transition zone, their natural extension is limited by urban development on the landward side and sea level rise on the seaward side. The primary threats to all mangrove species are habitat destruction; removal of mangrove areas for conversion to aquaculture, agriculture, and urban and coastal development; and overexploitation. Further, reductions in freshwater, nutrient enrichment through environmental pollution, and sea level rise also threaten mangrove species, particularly those with low salinity tolerance. It is also pertinent to rejuvenate species under significant threat (e.g., *Sonneratia griffithii* and *Brownlowia tersa*), especially those requiring stringent environmental conditions, such as low salinity, to grow (e.g., *Heritiera fomes* and *Nypa fruticans*). Considering the low species richness and low genetic diversity, it is imperative to assess site-specific information on mangroves to prevent their extinction. Furthermore, national-level policy making in India lacks a comprehensive understanding of how the various types of mangrove habitats along the coast function, in what social–ecological aspects they differ, and how those differences might be taken into account when planning for conservation. Thus, the current understanding of various components of Indian mangroves discussed here will be useful to streamline future research and effective formulation of long-term, integrated, ecosystem-based management for betterment of the sustainability of mangroves. On the whole, mangroves are still highly threatened in many locations, and this requires urgent research initiatives and management measures, without which a world without mangroves (Duke et al. 2007) will be a distinct possibility in the twenty-second century.

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Part III

Salinization Mechanisms and Impacts

Causes and Management of Root-zone Salinity and Sodicity in the Arid West Texas: Field-scale Experience

9

Girisha Ganjegunte and John Clark

Abstract

Salinity and sodicity of the root-zone in the Rio Grande Project area (RGPA) are serious threats to the long-term viability of the irrigated agriculture. This chapter focuses on causes and management of root-zone salinity and sodicity at the field scale. Available data suggest that salinity and sodicity in many agricultural fields in the region exceed the threshold levels for dominant crops (pima cotton, pecan, and alfalfa) with maximum values reaching as high as 17 $dS\ m^{-1}$ and 33 $mmol^{1/2}\ L^{-1/2}$, respectively. Efficacy of different tillage methods to modify seed environment and improve soil permeability to maintain salinity levels below the threshold is discussed. This chapter also evaluates various chemical approaches to correct root-zone sodicity management using irrigation water treatments and soil amendments. The review of results from various field studies suggests that adoption management practices to a large extent depend on profitability of the crop. While low-cost options such as seed environment modification are popular in pima cotton fields, more expensive methods such as tillage practices for profile modification and chemical treatments are used in remunerative crops such as pecans.

Keywords

Rio Grande Project Area · Soil salinity and sodicity · Salinity management practices · Seed environment modification · Tillage practices · Soil profile modification · Calcite · Gypsum · Elemental sulfur · Sulfur burner · Sulfuric acid · Polyacrylamide · Zeolites

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Abbreviation

CEC	cation exchange capacity
EC	electrical conductivity
ESP	exchangeable sodium percentage
LR	leaching requirement
PAM	polyacrylamide
RGPA	Rio Grande Project Area
SAR	sodium adsorption ratio
TDS	total dissolved solids

9.1 Introduction

Root-zone salinity is a major challenge to the long-term viability of agriculture in arid and semiarid regions of the world. Although salt-affected soils are found in a wide range of climatic condition, they are more common in dry regions due to inadequate leaching of salts out of effective root zone. Best available estimates indicated that about 1030 million hectares suffer from varying degrees of salinity and sodicity (FAO and ITPS 2015). About 30% of the land in the conterminous United States in drier western parts have moderate to severe salinity (Tanji and Wallender 2012). Causes include both natural processes and human-induced secondary salinization in irrigated lands in these arid and semiarid regions. The situation is no different in the basin irrigated by Rio Grande River, the fourth longest river that extends from southern part of Colorado to the Gulf of Mexico. Rio Grande River irrigates about 0.8 million ha in the United States and Mexico. According to Ghassemi et al. (1995), nearly 73% of the irrigated area in Rio Grande Basin is affected by salinity (expressed as total dissolved solids, TDS, or electrical conductivity, EC) and sodicity (expressed as sodium adsorption ratio, SAR, or exchangeable sodium percentage, ESP). Salinity has long been recognized as a major water quality problem throughout the Rio Grande Basin. Often Rio Grande River water salinity and sodicity levels exceed limits considered safe for sensitive crops (Grieve et al. 2012; Moyer et al. 2009). Salinity and sodicity problems in the region have resulted in reduction in irrigated acreage, shift in cropping pattern from high-value horticulture crop to low-value forage crops, loss in productivity of soils, and farm profitability.

9.2 Rio Grande Project Area (RGPA)

9.2.1 Irrigation Sources

This book chapter focuses on the far west Texas region covering El Paso County in the Rio Grande Basin. This region is also called as the Middle Rio Grande Basin or the Rio Grande Project Area (RGPA) referring to the area between Elephant Butte Reservoir and Fort Quitman (Fig. 9.1). The RGPA extends 165 miles north and 40 miles southeast of El Paso, Texas, and runs linear to the Rio Grande River in New Mexico and Texas with a maximum width of 7.2 km. The project irrigates about 178,000 acres (72,000 ha) in Dona Ana, Sierra, and Socorro counties in south-central New Mexico and County of El Paso in west Texas. Sixty percent of project lands are in New Mexico, and the remaining 40% are in Texas. Supplemental drainage provides water for 18,000 acres (7285 ha) in the Hudspeth County (Texas) Conservation and Reclamation District, which is downstream of El Paso. An international treaty between Mexico and the United States guarantees an annual allowance of 60,000 acre-feet (7.4 million m^3) of water for diversion to Mexico at the city of Juarez (USDOI 1980).

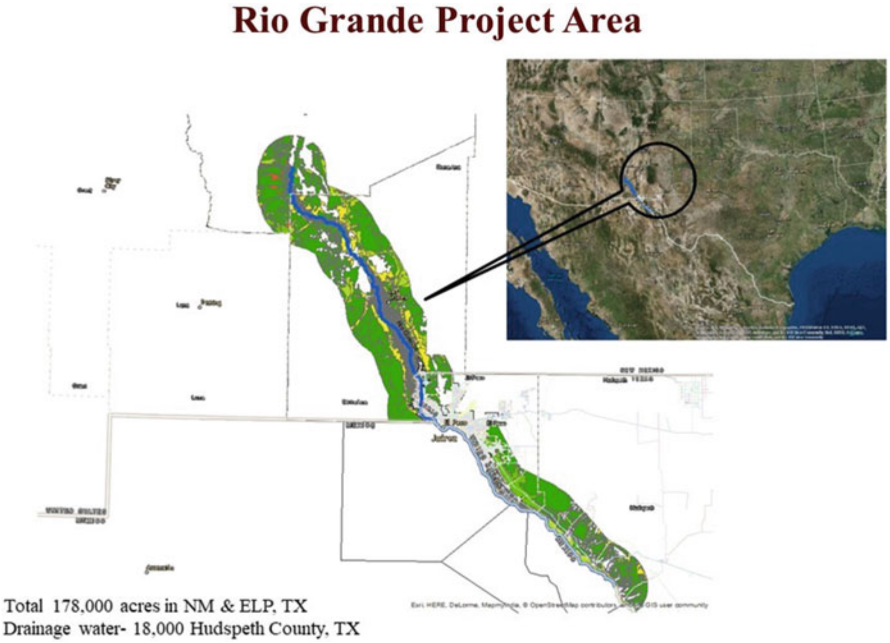

Fig. 9.1 Rio Grande Project Area covering parts of southern New Mexico and western parts of Texas. (Picture source: Ganjegunte)

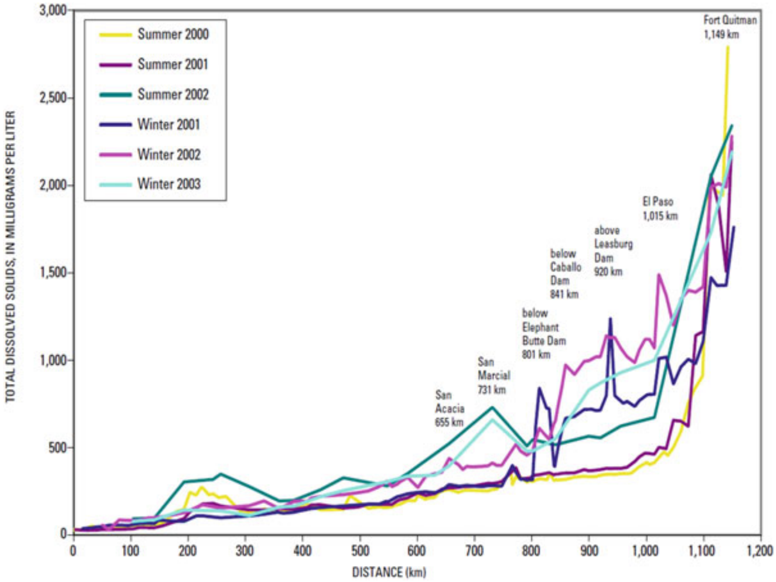

Fig. 9.2 TDS concentration during the winter and summer months from the headwaters in Colorado to Fort Quitman, Texas. (Picture source: Moyer et al. 2009)

The climatic conditions of the region especially precipitation and evapotranspiration have significant influence on the hydrology and associated water quality. Annual precipitation in the RGP is highly variable but averages around 15 cm; however, the annual potential evapotranspiration is about 194 cm. Thus, most of the precipitation occurring in the region is lost to atmosphere through evapotranspiration, and estimates suggest that about 75% of the water in the river is lost to evapotranspiration from headwaters to El Paso, TX. Consequently, salinity of the river increases four-fold between the headwaters and El Paso (Fig. 9.2) (Moyer et al. 2009). Geochemical and isotopic studies have indicated that in addition to evapotranspiration, other dominant processes such as upwelling of saline groundwater and mineral dissolution also contribute to increases in TDS of the river water (Moyer et al. 2009; Witcher et al. 2004; Szynkiewicz et al. 2015). Seasonal variation in TDS concentration in the Rio Grande is influenced primarily by the river flow that is influenced by inflow from tributaries, return flow from agricultural fields, municipal and industrial discharge, and groundwater discharge. Concentration of total dissolved solids is considerably elevated during the non-irrigation season because streamflow is the lowest and salts from agricultural drains, saline groundwater, and discharges from municipal wastewater treatment plants are not diluted. Conversely, during the irrigation season, salt concentration is considerably lower because of the increased streamflow levels in the Rio Grande (Table 9.1). Available data during the period 1934 to 1999 at measuring stations near El Paso, TX, indicate that the average monthly discharge and TDS during irrigation (May to September) and non-irrigation (October to Mar) are 24 and 5.7 $m^3\ s^{-1}$ and 763 and 1464 mg L^{-1}, respectively

Table 9.1 Irrigation quality of surface and groundwater sources

	Surface water Rio Grande River (Irrigation season)	Groundwater
EC (dS m^{-1})	1.31 ± 0.36	5.16 ± 1.41
pH	7.36 ± 0.41	7.73 ± 0.56
SAR ($mmol^{1/2}$ $L^{-1/2}$)	5.06 ± 3.66	8.03 ± 5.22
SARadj	5.12 ± 2.60	9.40 ± 3.76
B (mg L^{-1})	0.07 ± 0.09	0.4 ± 0.2
Ca (mg L^{-1})	69.7 ± 97.0	227.8 ± 115.2
K (mg L^{-1})	32.2 ± 54.4	16.6 ± 10.1
Mg (mg L^{-1})	19.0 ± 27.8	54.2 ± 27.7
Na (mg L^{-1})	184.8 ± 158.8	519.4 ± 240.5
F (mg L^{-1})	1.1 ± 0.9	1.9 ± 3.1
Br (mg L^{-1})	0.1 ± 0.1	1.2 ± 1.5
Cl (mg L^{-1})	184.6 ± 96.3	644.3 ± 325.2
NO_3 (mg L^{-1})	5.9 ± 3.6	–
PO_4 (mg L^{-1})	2.3 ± 3.2	–
SO_4 (mg L^{-1})	66.5 ± 66.2	428.7 ± 237.8
HCO_3 (mg L^{-1})	110.1 ± 23.5	141.5 ± 24.7

Data source: Ganjegunte

(Moyer et al. 2009). Using streamflow and TDS concentrations, the average TDS loads during irrigation and non-irrigation seasons are 1426 and 516 metric tons per day, respectively.

In addition to surface water sources, groundwater sources include two major aquifers in the Rio Grande Project area, namely, Mesilla Basin and Hueco Bolson (Fig. 9.3). Groundwater is used to supplement irrigation during the periods of drought. However, both Mesilla and Hueco Bolson contain brackish groundwater, meaning TDS concentration exceeds 1000 mg L^{-1} (Table 9.1). Groundwater from shallow zone (between 15 and 61 m) is highly saline due to saline groundwater upwelling and active interactions between shallow groundwater and return flow from agricultural field. The United States Geological Survey estimates that about 300,000 ac-ft (3.7 million m^3) of recoverable brackish water is stored in the shallow zone. Intermediate and deep zones of Mesilla Bolson aquifer have larger storage volumes than the shallow zone, but accurate estimates are not available (Burkstaller et al. 2001). Groundwater in the other aquifer, Hueco Bolson, is similar to Mesilla Bolson, but it holds much larger volumes. It is estimated that the shallow Rio Grande alluvium of Hueco Bolson holds about 1.73 billion m^3 of recoverable groundwater and the total brackish water storage in the aquifer is estimated at 22.67 billion m^3.

9.2.2 Crops

Main crops grown during the irrigation season in the region are pima cotton (*Gossypium hirsutum* L.), nut tree crop pecan (*Carya illinoinensis*) (Wangenh. K.

Fig. 9.3 Groundwater sources available in the Rio Grande Project Area. (Picture Courtesy: Michelsen)

Koch), fodder crop alfalfa (*Medicago sativa* L.), and vegetables such as green chili (*Capsicum annuum* L.) and lettuce (*Lactuca sativa* L.) during spring and summer. Onions (*Allium cepa* L.), alfalfa, and winter wheat (*Triticum aestivum* L.) are the main crops during winter. The threshold salinity for cotton, wheat, pecan, alfalfa, green chili, lettuce, and onion are 7.7, 6.0, 3.5, 2.0, 1.5, 1.3, and 1.2 dS m^{-1}, respectively (Grieve et al. 2012). Due to high evapotranspiration rates in the region, water requirements of these crops are far above the levels practiced in other parts of the country. Water requirements of pima cotton, alfalfa, and pecans during summer are 84, 152, and 152 cm, respectively. Spring lettuce and summer green chilis are irrigated with 76 and 140 cm, respectively, while during winter, wheat, onion, and alfalfa are irrigated with about 25.8, 143, and 23 cm, respectively. However, due to progressive salinization of the agriculture fields and changing market conditions, in the recent years, only two crops, pima cotton and pecan, are grown in more than 90% of the irrigated area.

9.2.3 Soils

Most of the agriculture in the El Paso region is practiced in the valley area on the banks of the Rio Grande River. Dominant soils in the agricultural areas belong to six soil series – Anapra (fine-silty over sandy, mixed, thermic, Typic Torrifluvents), Gila (coarse-loamy, mixed, calcareous, thermic, Typic Torrifluvents), Glendale (fine-silty, mixed, calcareous, thermic Typic Torrifluvents), Harkey (coarse-silty, mixed, calcareous, thermic Typic Torrifluvents), Saneli (clayey over sandy or sandy-skeletal, montmorillonitic, calcareous, thermic Vertic Torrifluvents), and Tigua

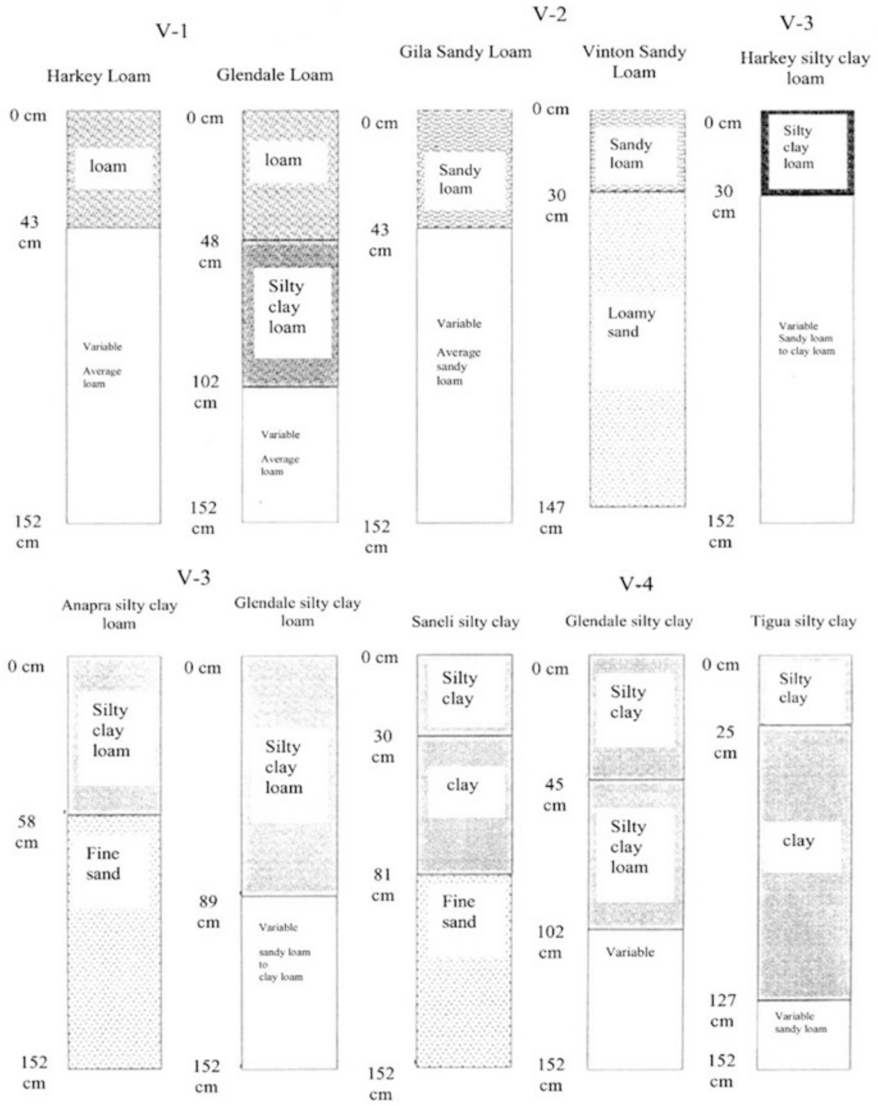

Fig. 9.4 Dominant soils in the RGPA valley. (Picture source: Miyamoto 2000)

(very fine, montmorillonitic, calcareous, thermic Vertic Torrifluvents) belonging to entisol order (USDA-NRCS 1971; Miyamoto 2000). For management, these can be grouped into four units, and typical cross section of these units is provided in Fig. 9.4. Soil units V-1 and V-2 generally have conducive soil texture for plant growth and facilitate deep roots. Soil groups V-3 and V-4 have fine-textured surface soils over loam or sandy subsurface. In some parts of the region, Harkey silty clay loam contains impervious clay layer occurring between 76 and 114 cm. The silty clay loam layer in these soils extends up to 91 cm, and even the tree crop pecan's roots remain in the upper 60 cm unable to penetrate sandy substrata. Management unit V-4, by far, is the most difficult group to manage salinity as the soils are either clay or silty clay which extends over 1 m deep into soil profile. Depth to water table in most parts of the valley is about 2 m.

Smectites are the dominant clay minerals in these soils, and upon drying these can shrink by 15–20%. Formation of soil cracks in valley soils improves infiltration initially, but permeability of these soils decreases drastically as the cracks are sealed upon irrigation. Saturated permeability of V-3 and V-4 soils is considered as low ranging 0.15 to 0.51 cm per hour and has high water retention capacity of 45%. All the valley soils have pH values around 8, and in intensively cultivated soils, the pH ranges from 7 to 8 depending upon CO_2 partial pressure of the root zone. These agriculturally important valley soils are often deficient in nitrogen (N), zinc (Zn), iron (Fe), and Manganese (Mn).

A majority of the irrigated area in the region contain calcite ($CaCO_3$) and gypsum ($CaSO_4.2H_2O$) in the top 75 cm depths. Concentrations of calcite and gypsum in these soils can reach 10% and 2.5% by weight, respectively. However, low solubility of calcite and poor permeability of surface layers limiting solubilization of gypsum limit Ca release to soil solution for countering Na in sodic soils. Additional measures are required to tap these native Ca sources. Native Ca minerals also interfere with the cation exchange capacity (CEC) and exchangeable sodium percentage (ESP) measurements due to fixation of NH_4 of ammonium acetate used for ESP and CEC determination by smectite clays and continued release of Ca from native minerals in to ammonium acetate solution resulting in under estimation of ESP (Ganjegunte et al. 2006). Under these conditions, estimation for ESP from sodium adsorption ratio (SAR) is calculated using the following empirical equation (Richards 1954):

$$\begin{aligned}\mathrm{ESP_e} = {} & [100 \times (-0.0126 + 0.01475 \times \mathrm{SAR_e})] \\ & /[1 + (-0.0126 + 0.01475 \times \mathrm{SAR_e})]\end{aligned} \tag{9.1}$$

where $\mathrm{ESP_e}$ is estimated exchangeable sodium percentage and SARe is sodium adsorption ratio of soil saturated paste extract which is calculated from the following equation:

$$\mathrm{SAR_e}\left(\mathrm{mmol}^{1/2}\mathrm{L}^{-1/2}\right) = [\mathrm{Na}^+]/\left[\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}\right]^{1/2} \tag{9.2}$$

where Na, Ca, and Mg represent millimolar concentrations (mmol L^{-1}) of the respective ions.

9.3 Root-zone Salinity and Sodicity

Irrigation history in the Rio Grande Project area dates back to the 1800s when a system of acequias or irrigation ditches were used to irrigate. Subsequent colonization and rapid development placed high demands on water supplies resulting in

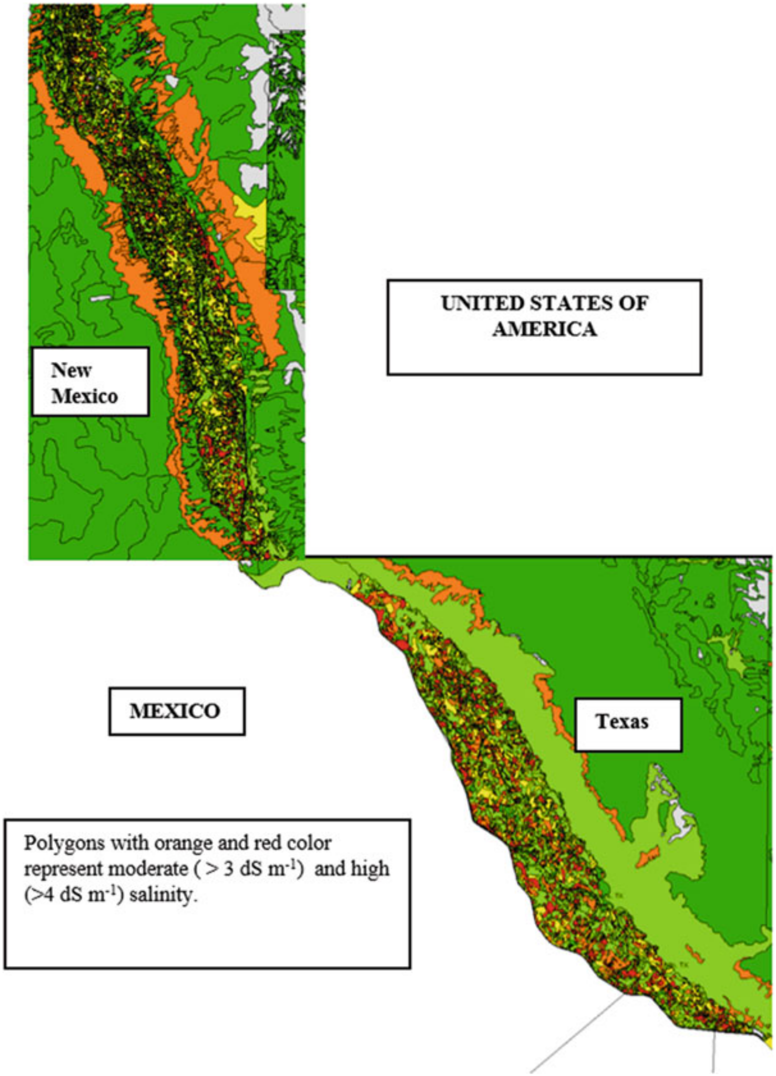

Fig. 9.5 Soil salinity in the upper 75 cm of root zone in the Rio Grande Project area during the 1960s. (Picture source: USDA-NRCS 1971)

completion of current irrigation distribution system, and active intensive irrigation for production in the valley began since 1938. However, within two decades of active intensive irrigation, salinity and sodicity in many areas exceeded the threshold values of 4 dS m^{-1} and 13 $mmol^{1/2}$ $L^{-1/2}$, respectively, making the soils saline and sodic. This is evident from Fig. 9.5 that provides the spatial distribution of levels within the RGP area in the 1960s (USDA-NRCS 1971). While the salinity levels in V-1 and V-2 were low and not a major concern (green areas), in groups V-3 and V-4,

Table 9.2 Salinity and sodicity in valley soils during 1978 and 1997

Soil series	Group	Texture	1978	Salinity (EC_e) 1997			Sodicity, SAR 1997		
			Mean	Mean	Max	CV	Mean	Max	CV
			dS m^{-1}			%	$mmol^{1/2}L^{-1/2}$		%
Harkey	V-1	Loam	1.4	1.5	2.1	30	6.4	7.9	19
Saneli	V-3	Silty clay loam	2.8	1.5	2.5	32	–	–	–
Glendale	V-3	Silty clay loam	3.6	1.7	3.7	47	6.1	8.7	24
Glendale	V-4	Silty clay	2.7	36.9	45.7	34	27.5	31.0	12
Glendale	V-4	Silty clay	3.6	3.6	5.0	17	8.1	8.8	9
Glendale	V-4	Silty clay	–	4.6	8.0	37	10.0	17.0	26
Tigua	V-4	Silty clay	4.4	4.5	6.3	24	10.0	15.4	28

Data source: Miyamoto (2000)

Table 9.3 Salinity and sodicity in four major series of the valley

Soil series	Salinity (EC_e)			Sodicity (SAR)		
	Mean	Max	CV	Mean	Max	CV
	dS m^{-1}		%	$mmol^{1/2}$ $L^{-1/2}$		%
Pecan field (2010)						
Glendale	2.81	6.12	55.09	6.12	12.00	47.65
Harkey	3.31	5.49	51.74	7.17	12.09	46.02
Saneli	3.62	9.17	74.56	7.41	20.36	79.27
Tigua	4.56	7.86	44.29	10.20	17.67	50.01
Cotton field (2012)						
50% Tigua, 25% Saneli, 15% Harkey 10% Glendale	5.15	17.83	81.75	14.69	32.98	63.20

Data source: Ganjegunte and Braun (2011) and Ganjegunte et al. (2014)

salt accumulation was a major concern (orange and red). Subsequent studies conducted confirmed further increases in salinity and sodicity in all the valley soils including V-1 and V-2 groups (Table 9.2).

However, agronomic management practices have significant effects on salinity and sodicity distribution for the same soils under different crops. Studies conducted in 2010 and 2012 on salinity and sodicity assessment in same soil series showed much higher levels in cotton fields than pecan fields (Ganjegunte and Braun 2011; Ganjegunte et al. 2014) (Table 9.3).

Thus, decades of irrigation with large quantities of surface and groundwater supplies having elevated salinity and sodicity on soils with low permeability especially in surface horizons, inadequate drainage, and high-water table coupled with high evapotranspiration rates have contributed to saline-sodic root zone in the agricultural areas.

9.4 Salinity and Sodicity Management Practices at the Field Scale

Salinity management practices discussed in this chapter at the field scale can be grouped as physical (tillage practices to modify seed environment and improve leaching of salts) and chemical methods (to improve irrigation water quality and correct soil sodicity hazards). In addition, growers use biological measures such as selection of salt-tolerant cultivars and grafting high-yielding pecan scions on salt-tolerant root stocks that are not included in the discussion. Choice of salinity and sodicity management practices largely depends on soil profile, salt sensitivity of the crop, and economic factors such as cost of salinity management and cost recovery. Pecan is a salt-sensitive tree nut crop that is highly remunerative, and, therefore, growers take many ameliorative measures to actively manage salinity and sodicity. Whereas the other major crop, cotton is considered as a salt-tolerant crop and due to uncertainties of farm revenue owing to fluctuations in lint prices, cotton growers generally don't actively manage salinity in these fields. However, there are some regular tillage practices cotton growers practice to keep the salinity under threshold level especially in the early stages of the crop.

9.4.1 Leaching

Valley soil groups V-1 and V-2 have good permeability, and application of leaching requirement (LR) or leaching fraction (LF) in addition to crop requirement can reduce accumulation of salts in the effective root zone. Leaching approach to control salinity has the following assumptions:

- The site soil is permeable enough to allow necessary water infiltration and drainage.
- The salt carried into the field is being leached quantitatively.
- Crops respond to the mean salinity of the root zone.

There are several equations that can be used to calculate leaching requirement (LR) to control salinity of the root zone. The choice of equation depends on the accuracy of data on crop consumptive use, texture of soil, soil permeability, salinity of irrigation water, root-zone salinity, threshold salinity of the intended crop, and plant responses to root-zone salinity. One of the popular LR equations commonly used when good quality water is available is provided below:

$$\mathrm{LR} = (\mathrm{D_w} - \mathrm{ET})/\mathrm{D_w} = \mathrm{EC_w}/\mathrm{EC_d} \tag{9.3}$$

or

$$\mathrm{LR} = \mathrm{EC_w}/(2(\mathrm{n}+1)\ \mathrm{EC_e} - \mathrm{nEC_w}) \tag{9.4}$$

where LR is the leaching requirement, D_W the depth of irrigation, ET the consumptive use, EC_w the electrical conductivity of irrigation water, EC_e the mean electrical conductivity of the root zone measured in the soil saturation extract (Rhoades and Miyamoto 1990), and n is an empirical coefficient. Typically, n = 2 in sandy soils, and n = 1 in clayey soils (Rhoades 1974).

If the irrigation water salinity exceeds 2 dS m^{-1} and gypsiferous as is the case in many parts of the RGPA, the salinity of the drainage water does not increase linearly with the evaporation, due to precipitation of Ca and SO_4 as gypsum. In this case LR is calculated by using the following equation:

$$\mathrm{LR} = (\mathrm{D_w} - \mathrm{ET})/\mathrm{D_w} = \mathrm{EC_w}/[(1 - \mathrm{p})\ \mathrm{EC_d}] \tag{9.5}$$

or

$$\mathrm{LR} = \mathrm{EC_w}/(1 - \mathrm{p}) * \left([2(\mathrm{n} + 1)\ \mathrm{EC_e} - \mathrm{nEC_w}\right) \tag{9.6}$$

where p is the proportion of salts precipitated, which can be measured by evaporating the gypsiferous water to the level comparable to 1/LR and checking the changes in conductivity.

Another derivation of Rhoades (1974) equation that considers threshold salinity of the intended crop is provided below:

$$\mathrm{LR} = \mathrm{EC_w}/(5 \times \text{Threshold } \mathrm{EC_e} - \mathrm{EC_{iw}}) \tag{9.7}$$

where LR is leaching requirement; EC_{iw}, electrical conductivity of irrigation water; and EC_e, threshold electrical conductivity for a given yield level of the crop.

For example, if water has a salinity of 2.5 dS m^{-1}, then to get 100% yield of cotton, the amount of irrigation water required including leaching fraction is calculated as follows:

$$\mathrm{LR} = 2.5/(5 \times 7.7 - 2.5) = 0.07 \text{ OR } 7\%.$$

Therefore, if cotton water requirement is 84 cm, leaching requirement is 5.8 cm, and the total irrigation required will be 89.8 cm.

9.4.2 Tillage Practices to Manage Salinity

These measures involve either modifying the microclimate to facilitate seed germination and stand establishment or improving permeability especially in fine-textured surface soils (e.g., soils belonging to V-3 and V-4 groups).

9.4.2.1 Modifying the Seed Environment

This method of managing salinity is most commonly used in row crops such as cotton. Although tolerant to salinity at later stages, cotton is vulnerable to salt stress in the early stages. In many cotton fields in the RGP area, salinity especially in the surface layers can be detrimental to germination and emergence of seedlings

Fig. 9.6 Manipulating seed environment to facilitate germination and seedling emergence. (Picture source: Ganjegunte)

(Ganjegunte et al. 2018). To overcome this high salinity, the microenvironment surrounding the seed is manipulated as follows. After land preparation, at the time of planting usually in late April or early May, seeds are placed about 7.5 cm deep in the center of ridges spaced 1 m apart and immediately irrigated with about 15 cm of irrigation water. This results in solubilization of most of the salts present in the top soil and accumulation on the top of the ridge along with evaporating water. After about a week, the "hill" of the ridge containing most of accumulated salts is knocked off into furrows (Fig. 9.6). As a result, the soil immediately surrounding the seed will have less salinity compared to that in the furrow. This ensures successful germination of seeds and emergence of seedlings after a few days. Later stages of cotton crop are less vulnerable and can withstand higher levels of salinity stress.

9.4.2.2 Improving Soil Permeability

Application of leaching fraction will be ineffective if the soil permeability is low. This applies to soil profiles limited by permeability, which constitute about 70% of the agricultural area in the valley. This is especially true for valley soil groups V-3 and V-4 that have high clay contents limiting adequate drainage and percolation. In addition, soil compaction either by the frequent use of heavy farm equipment is an inevitable consequence in agricultural fields. This gets compounded by soil

Fig. 9.7 Shallow ripper. (Photo source: Texas A&M AgriLife Research Center at El Paso)

aggregate breakdown commonly observed in saline-sodic soils. Therefore, improving soil permeability is a necessary step for leaching salts. The primary goal of soil improvements in low-permeability soils is to enhance water infiltration, water penetration, salt leaching, soil water storage, and availability.

9.4.2.2.1 Shallow Ripping

Shallow ripping can be used to break clay pans commonly found in silty clay loam soil in surface depths. Curved ripper shanks (Fig. 9.7) that can penetrate up to 60 cm are the most commonly used tool in shallow ripping. Shallow ripping decreased soil salinity at 0–30 cm, 30–60 cm, and 60–90 cm depths by 36, 37, and 34%, respectively (Fig. 9.11). However, if the clay layer occurs below 75 cm or in areas near the tree line where roots interfere with the operation, shallow ripping has limited effect. Another disadvantage with shallow ripper is that it leaves large clay clods and requires a lot of effort to level the land.

9.4.2.2.2 Minimum-till Subsoiling

This tool minimizes surface ripping and is effective in breaking the clay in subsurface up to a depth of 75 cm (Fig. 9.8). The goal is to reduce clods and create cracks in surface layers that facilitate water movement and leaching of salts. If the surface layers are clayey, then top dressing with sand is highly recommended. Sand top dressing helps in filling the cracks opened by subsoiler and thereby keeping them open for extended period. Another advantage of using the straight shanks for subsoiling is pruning of secondary roots that stimulates fibrous tertiary root production. Studies have suggested that if carried out annually this approach can decrease salinity in 30–60 cm and 60–90 cm by 23% and 52%, respectively (Fig. 9.11).

9.4.2.2.3 Deep Chiseling

Deep chiseling can break impermeable calcic or gypsic layer commonly found in many upland soils of the region (Fig. 9.9). This tool has a reach down to a depth of 1.5 m. Once the impervious subsurface layer is fractured, the deep chiseling approach is often combined with the shallow ripping or minimum-till subsoiling to maintain the permeability for extended periods. Studies have shown that deep

Fig. 9.8 Minimum-till subsoiler. (Photo Courtesy: Texas A&M AgriLife Research Center at El Paso)

Fig. 9.9 Deep chiseler. (Photo Courtesy: Texas A&M AgriLife Research Center at El Paso)

chiseling decreased the soil salinity by 44%, 46%, and 39% at 0–30 cm, 30–60 cm, and 60–90 cm depths, respectively (Fig. 9.11).

9.4.2.2.4 Excavation to Modify Soil Profile

Excavation creates drainage in soils that have thick clay surface horizons and takes advantage of occurrence of sandy layers at deeper depths. The process involves a larger excavator to mix surface clays layers with subsurface sand layers to create a loamy texture in excavated areas running parallel to tree lines (Fig. 9.11). This method is used in soils that have clay at the surface and sand in the subsurface (Fig. 9.10). The goal is to create loam texture in the trenched area. A deep trench is created along the dripline of one side of the tree rows. Depth of the excavation is generally

Fig. 9.10 Excavation to modify soil profile. (Photo source: Texas A&M AgriLife Research Center at El Paso)

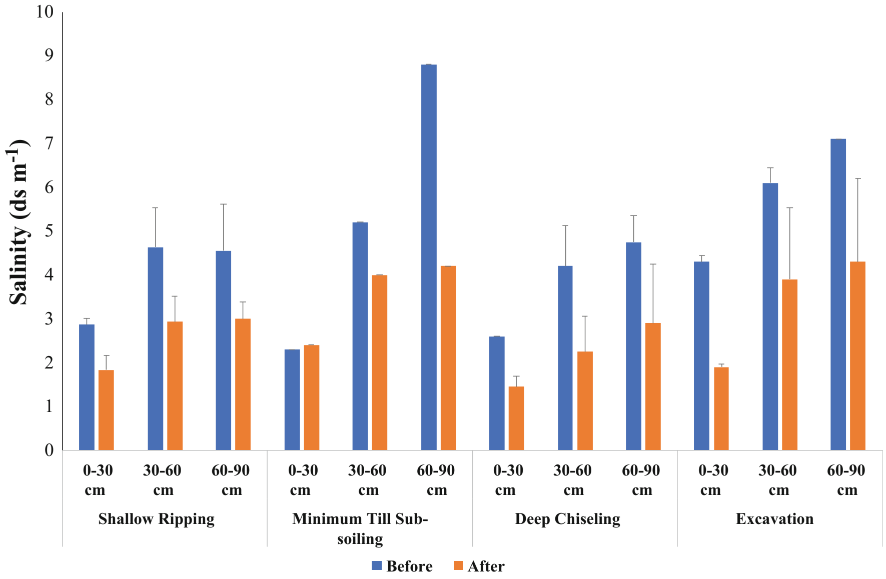

Fig. 9.11 Effects of different tillage operations on soil salinity at different depths. (Data source: Miyamoto and Nesbitt 2011)

twice the depth of the clay layer, and the width can be up to a 1.2 m. In deep clay loam or silty clay soils, trenching is generally combined with minimum-till chiseling with sand top dressing. Since the trees are spaced 12 m apart and roots are confined to 2.5 m radius around the trees, land in the intra-row can be worked with the excavator. If clay layer extends deeper than excavated depth or if the sand layer is not present under the clay, this method does not work. In which case sand needs to be brought from external source (this being a desert ecosystem, there is plenty of sand dunes available in nearby areas, and often growers own land in multiple locations, which may include sand dunes). Because of the expense, it is recommended that one side of the tree on alternative rows is excavated during the first year and the other side is excavated 4 years later. This is an effective approach to reduce salinity in salt-affected pecan orchards. Even after 3 years after soil profile modification by excavation soil salinities at 0–30 cm, 30–60 cm, and 60–90 cm decreased by 56%, 36%, and 39%, respectively (Fig. 9.11).

9.4.3 Lowering Water Table

To lower the water table in the agriculture fields, the local irrigation district has constructed open drains or trenches that receives subsurface drainage from agricultural fields at a depth of 2.5 m along the contours (Fig. 9.12). These structures require constant maintenance to control invasive plant species and prevent clogging of drain tubes coming out of agricultural fields. Some of the fields in the El Paso valley have

Fig. 9.12 Open drains to lower the water table. (Photo Source: Ganjegunte)

experimented with subsurface drains without much success. The reasons for failure of subsurface drains included volume of drain far exceeding the designed capacity because of canal and river flow seepage or heavy storm that commonly occurs in the region. This created perched high-water table resulting in worsening of salinity situation in the root zone.

9.4.4 Chemical Methods

9.4.4.1 Gypsum

Chemical methods are required for lowering sodicity to improve its soil permeability and leaching of salts. Soils affected by sodicity have lower permeability due to deflocculation of soil aggregates resulting in dispersion of clay particles and plugging of pores creating surface crusting, reduced infiltration, and hydraulic conductivity. Reducing sodicity of soils in the root zone can be achieved by reducing the Na concentrations on soil exchange complex by increasing the supply of available calcium either through external sources such as application of gypsum ($CaSO_4.2H_2O$) or utilizing the native Ca minerals already present in the agricultural soils of the region. The amount of gypsum application depends on the severity of the sodicity and the target ESP level. As a rule of thumb, about 3910 kg of gypsum is required to reduce Na by 1 $cmol_{(+)}kg^{-1}$ in a ha-0.3 m slice. For example, if initial ESP of an affected soil having a CEC of 25 $cmol_{(+)}kg^{-1}$ is about 30%, then to reduce it to an acceptable level of 15%, the amount of gypsum required for ha-0.3 m would be 15,000 kg. In the El Paso region, the current cost of gypsum is about $36.5/1000 kg and therefore the gypsum cost alone would be $532/ha-0.3 m. A typical farmer owns hundreds of hectares of land, and correcting sodicity problem by external application of Ca sources can be quite expensive over time.

9.4.4.2 Elemental S

To reduce the cost and to take advantage of the Ca sources that are already present in the soil profile, application of elemental sulfur (S) is recommended for valley soil types V-1 and V-2, which have permeable surface horizons. As mentioned earlier most soils in the region have up to 10% $CaCO_3$ by weight in the upper 75 cm that covers effective root zone of major crops grown in the region. Application of elemental sulfur results in production of sulfuric acid through the action of soil microbes as per the reaction provided below:

$$2S + 3O_2 \underset{\text{mediated oxidation}}{\overset{\text{Soil Microbially}}{\rightarrow}} SO_3 \tag{9.8}$$

$$SO_3 + H_2O \rightarrow H_2SO_4 \tag{9.9}$$

This sulfuric acid reacts with calcium carbonate/calcite present in the soil profile to produced gypsum, water, and carbon dioxide as follows:

$$CaCO_3 + H_2SO_4 \rightarrow CaSO_4 + H_2O + CO_2 \tag{9.10}$$

The recommended rate of S application is about 727 kg for reducing 1 $\text{cmol}_{(+)}\text{Na kg}^{-1}$ in ha-0.3 m volume. However, as it is evident from the reactions, that supply of oxygen or good aeration is a prerequisite for the conversion of S to sulfuric acid. In addition, this process is a slow biologically mediated oxidation that takes long time. Elemental S is also expensive costing about $462/1000 kg, and at the prevailing price of S, it would cost $1250 to reduce ESP from 30% to 15% in a ha-0.3 m slice. Thus, high cost for a method is not always effective and is not appealing to many growers in the region especially in fields that have V-3 or V-4 soil types.

9.4.4.3 Sulfuric Acid

Therefore, in pursuit of effective methods, in $CaCO_3$-rich soils that are severely affected by high sodium concentration, growers resort to application of concentrated sulfuric acid to water in the field canals that gets diluted as it makes its way to the affected field (Fig. 9.13). This diluted sulfuric acid is strong enough to react with the calcite (evident from effervescence in treated field) but does not affect plant roots. The sulfuric acid used for treating irrigation water is 92% pure and is a by-product from industrial processes, which costs $253/1000 kg. Growers apply 3300 kg (1800 L) concentrated H_2SO_4 (four split applications of 825 kg) into 1 ha during the irrigation season at a cost of about $830. Studies have confirmed that when applied

Fig. 9.13 Acidifying irrigation water to convert native $CaCO_3$ to gypsum. (Picture source: Ganjegunte)

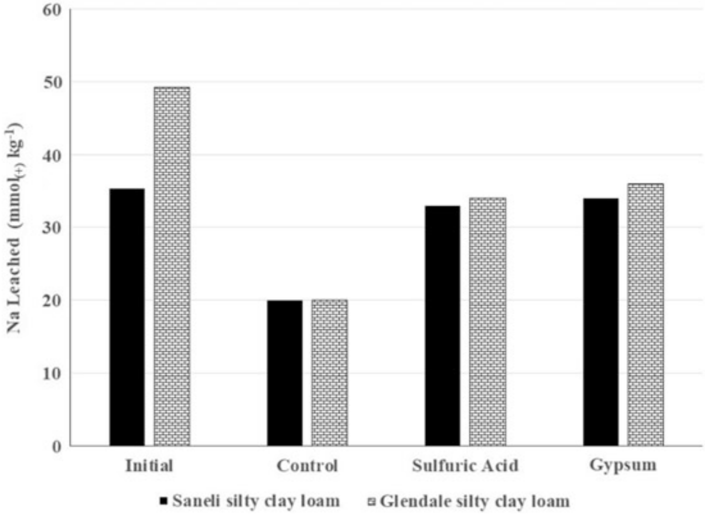

Fig. 9.14 Application of sulfuric acid and gypsum at 11 $mmol_{(+)}$ kg^{-1} to Saneli silty clay loam and 22 $mmol_{(+)}kg^{-1}$ to Glendale silty clay loam soils in El Paso removed similar amounts of Na. (Data source: Miyamoto and Stroehlein 1986)

at equal molar concentrations, application of sulfuric acid to soils containing $CaCO_3$ performed similar to or better than external application of Ca through gypsum (Fig. 9.14).

Application of concentrated H_2SO_4 in this manner is highly effective in converting calcite to gypsum but presents a potential risk to agricultural workers. Temperatures in the region during the irrigation season exceed 40 °C, and the agriculture laborers often ignore the use of protective gear (gloves, safety coat, goggles, etc.) required to handle concentrated H_2SO_4. Unsafe application of sulfuric

Fig. 9.15 S burner used in a pecan field in the El Paso Valley. (Picture source: Ganjegunte)

acid in agricultural fields has led to many injuries and liability lawsuits (based on discussions with local growers). Therefore, in the recent years, acidification of irrigation water using sulfur burner is gaining popularity.

9.4.4.4 Sulfur Burner

The S burner, as the name suggests, burns elemental S in a controlled way to produce H_2SO_3 and eventually H_2SO4 (Fig. 9.15). Conversion of S is described in the following equations:

$$S + O_2 \rightarrow SO_2(\text{sulfur dioxide}) \tag{9.11}$$

$$H_2O + SO_2 \rightleftarrows H_2SO_3(\text{sulfurous acid}) \tag{9.12}$$

$$H_2SO_3 + O_2 \rightleftarrows H_2SO_4(\text{sulfuric acid}) \tag{9.13}$$

The resultant acid is mixed with untreated irrigation water in the field ditch. The dilute H_2SO_4 (concentration can be adjusted) produced by S burner is less corrosive than the concentrated H_2SO_4 (18 M) that is currently used to acidify irrigation water by farmers.

Ganjegunte et al. (2018) evaluated the performance of S burner in a cotton field dominated by clay-textured calcareous sodic soils. After 1-year irrigation (84 cm) with S burner-blended water, the SAR of the field reduced significantly in all five depths studied (Table 9.4).

Furthermore, this reduced sodicity facilitated greater infiltration and hydraulic conductivity in the root zone, which in turn resulted in lower salinity levels in the upper 30 cm (Fig. 9.16) (Ganjegunte et al. 2018).

9.4.4.5 Polymers

Polymers such as polyacrylamide (PAM) have been successfully utilized to decrease surface runoff, reduce soil erosion in furrow irrigation, and improve infiltration rates (Lentz and Sojka 2009). However, their effects on improving infiltration and

Table 9.4 Effect of S burner-treated blended irrigation on soil sodicity in a clayey cotton field

	Sodium adsorption ratio (SAR)	
	Initial	After S burner irrigation
Depth	mmol$^{1/2}$ L$^{-1/2}$	
0–15 cm	12.7–16.7	4.9–16.0
15–30 cm	11.8–20.5	9.8–18.0
30–45 cm	12.1–23.9	9.8–18.6
45–60 cm	11.4–23.1	11.8–19.7
60–75 cm	10.8–21.6	4.0–19.8

Data source: Ganjegunte

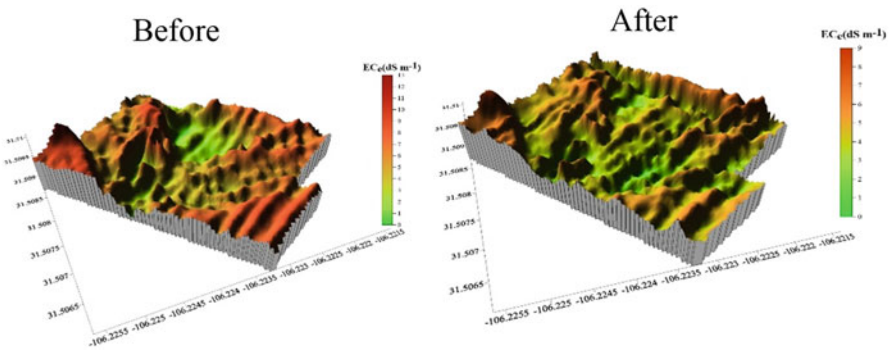

Fig. 9.16 Reduction in soil salinity at 0–30 cm depth in a saline-sodic cotton field irrigated with S burner-treated water. (Picture source: Ganjegunte)

hydraulic conductivities in saline-sodic soils are not well understood. Valley soils in the El Paso area are characterized by shrink-swell smectite clays, and before the onset of irrigation, huge cracks are visible in the agricultural fields. The preferential flow in these cracks may be exploited for improving leaching of salts. In addition, improvements in soil permeability created by different tillage practices generally last for a season or two. If the favorable conditions created by tillage can be extended or preferential flow in the cracks can be exploited by the use of polymers, it would reduce the cost of salinity management. Ganjegunte et al. (2011a) demonstrated that application of PAM at the rate of 10 ppm only once during the year with the first irrigation water can improve soil permeability, solubilize native Ca sources to counter sodicity, and leach salts. Furthermore, their results indicated that PAM extended the duration of improved permeability from 1 to 3 years, which can help in significantly reducing the salinity management costs.

9.4.4.6 Zeolites

As mentioned in the previous sections on irrigation water quality, all the major water supplies in the region contain elevated sodium concentrations that are responsible for increased sodicity of root zone. The most popular method of reducing the Na concentration in water for municipal and industrial applications has been reverse osmosis, but this method is very expensive for treating irrigation water. Treatment of sodic waters with Ca- or K-rich clinoptilolite zeolites can help in improving its irrigation quality. Zhao et al. (2008) and Ganjegunte et al. (2011b) successfully demonstrated reduction in SAR of irrigation water (by removing excess Na by exchanging with Ca or K) from a high level of 30 to an acceptable level of 10 $\mathrm{mmol}^{1/2}\ \mathrm{L}^{-1/2}$ by using zeolites. By using column studies, they estimated that a metric ton (1000 kg) of Ca-zeolite and K-zeolite can treat 16,000 and 60,000 L of irrigation water, respectively. They estimated that the cost of treating 1000 L of high SAR irrigation waters ranged from \$1.25 to \$6.25. However, this cost can be significantly reduced by regenerating the spent zeolites.

9.5 Summary

Rio Grande Project area that is located in the desert west of Texas receives low precipitation but has very high evapotranspiration. Agriculture in RGPA depends on availability of irrigation water. Unfortunately, all the available irrigation water sources in the region have elevated salinity and sodicity. Decades of irrigation with saline-sodic waters on fine-textured valley soils has resulted in salinization of a majority of the irrigated area in the RGPA. Salinity and sodicity issues in agricultural areas have led to reduction in irrigated acreage, shift in cropping pattern from high-value horticulture crop to low-value forage crops, loss in productivity of soils, and farm profitability. Among the various salinity management practices, seed environment modification is widely practiced in cotton fields, while different physical and chemical methods of salinity and sodicity management are used in pecan fields. Evaluation of salinity control measures indicated that choice of management practices depends on crop salt tolerance, cost of salinity control, and farm profitability. Lessons learned from this field-scale experience of salinity management can be applicable to semiarid and arid regions throughout the world.

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Salinity-induced Physiological and Molecular Responses of Halophytes

10

Ashwani Kumar, Anita Mann, Charu Lata, Naresh Kumar, and P. C. Sharma

Abstract

The last few decades has seen a relentless increase in the various forms of land degradation. Different forms of salinity, especially the irrigation-induced secondary salinity, pose formidable constraints to the management of agricultural lands across the world. Although several engineering, agronomic and biological solutions have been suggested for reviving the productivity of salt-impaired lands, of late there is increased emphasis on plant-based solutions for reducing the management costs in an environment-friendly manner. Plant adaptation to abiotic stresses is controlled by cascades of events at the biochemical and molecular level. Halophytes are the plants adapted to grow and reproduce in salt-rich environments, making them model species for studying the physiological and genetic bases of salt tolerance and potentially novel crops for generating revenue from deteriorated salty lands otherwise unsuitable for various agricultural uses. In this chapter, we have attempted to provide a brief overview of salt tolerance in halophytes. Different morphological, physiological and genetic traits underpinning high salinity tolerance in these economically important plants have been delineated. Prospects of further improvements in the salt tolerance capacity of halophytes through genomics and transgenic approaches have been explored.

Keywords

Halophytes · Salinity · Osmoregulation · ROS scavenging · Ion homeostasis

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In the last few decades, human-induced environmental degradation has attained serious levels in different parts of the world, posing threats to ecological balance and food security. While global population and the attendant increase in food demand continue to rise, productive croplands are shrinking at an accelerated rate with inter-sectoral competition for land use and various forms of degradation identified as the major drivers of land loss. As the competition for land and freshwater use intensifies, agriculture will increasingly be pushed to marginal areas (FAO 2011; FAO and ITPS 2015). This state of affairs has necessitated reclamation and management of less productive, degraded and abandoned lands for crop production and other agricultural uses to address the intertwined concerns of food security and environmental sustainability. Among various biotic and abiotic constraints known to debilitate soil health and crop productivity, abiotic stresses like temperature extremes (too low or high), salinity/sodicity and associated problems (e.g. waterlogging), extended periods of water deficit, water stagnation on surface and in root zone and heavy metal toxicity are increasingly becoming a significant concern across the globe (Sharma and Singh 2017a, b). It is now undeniable that climate change and its inevitable direct and indirect consequences inter alia, erratic rainfall, high temperature, glacial melt, depleting fresh water, repeated droughts and floods and emergence of new insect-pests and diseases, have become the new normal, threatening human society in a myriad of ways. Many of these changes could have wide ranging ramifications for sustainable natural resources management, especially in areas suffering from constraints like high aridity, freshwater scarcity and salinity (Dasgupta et al. 2015; John et al. 2005). Aberrant rainfall and temperature regimes can accelerate the rates of soil and water salinization manifold in regions where these problems are still in an incipient state.

Like other environmental stresses, salinity—a generic term to refer to salt-affected soils and low-quality salty waters—often takes a heavy toll on soil quality and crop yields regardless of the agroclimatic conditions, though salt-induced problems are relatively more profound in (semi)arid than in (sub)humid regions (Sharma and Singh 2015). In addition to immediate (and direct) adverse impacts on soils and crops, presence of excess salts and/or exchangeable sodium sets in motion a series of events leaving ultimately a trail of destruction that becomes noticeable after years or decades. This implies the need to employ appropriate research and management interventions in the beginning to nip the problem in the bud: the recent 'Aral Basin disaster' (Micklin 2007) remains the grim reminder of unforeseen consequences of relentless salinization on a regional scale. Although salinity is known to have been a cause of human misery since ancient times, the last few decades have seen a phenomenal rise in the problem in both irrigated and dryland areas of the world where irrigation mismanagement (Houk et al. 2006; Singh 2009; Smedema and Shiati 2002) and land clearing (Pannell and Ewing 2006; Walker et al. 2002), respectively, have rendered vast stretches of once productive lands virtually barren. Aforementioned facts clearly reflect the need for managing the salinity problem at an early stage, before it attains epic proportions and becomes a non-manageable environmental burden. This logic stems from the fact that various agronomic and biological management options provide best results in moderately salt-affected conditions, while strenuous efforts are needed for reviving the productivity of severely salt-impaired areas.

Global extent and severity of salinity problem are evidenced by the fact nearly a fifth of total global irrigated land area (~45 million ha) is afflicted by excess salts to varying degrees. Furthermore, an estimated 1.5 M ha area virtually goes out of production annually in various irrigation schemes throughout the world (Munns and Tester 2008; UNCCD 2017), a trend likely to wreak havoc to irrigated agriculture as half of the total arable lands are predicted to become salinized in the next three decades (Mahajan and Tuteja 2005). Although reliable estimates are not available, many rainfed farming areas are also hard hit by salt-induced land degradation; millions of hectares of arable lands have either become less suitable or gone out of cultivation due to excessive salt build-up in Australia alone (Pannell and Ewing 2006; Ridley and Pannell 2006). It may be a coincidence that salinity onslaught is particularly alarmingly high in regions and countries currently witnessing a rapid demographic expansion including China (Li et al. 2014) and Indian sub-continent [Bangladesh (1 M ha; Hossain 2010), India (6.73 M ha; Sharma and Singh 2015) and Pakistan (3–6 M ha; Qureshi et al. 2008)], posing grave risks to their food security and agricultural sustainability.

Plant adaptation to abiotic stresses is controlled by cascades of events at the biochemical and molecular level. As a result, several defence mechanisms are triggered to re-establish homeostasis and protection of proteins and membranes. On the molecular level, several gene families are responsible for the induction of stress-related defence pathways. In this backdrop, it is increasingly being realized that affordable and feasible solutions are urgently required to harness the productivity of SAS under a changing scenario characterized by the challenges like freshwater scarcity. Although a number of high-yielding and salinity-tolerant genotypes are available in different crops, they often fail to grow under extreme salinity necessitating the identification and development of alternative crops that can be produced in harsh conditions. In this situation, one of the ways is to make and select the crop plants genetically engineered to sustain their growth and productivity in such challenging environments. This requires exploring gene pool of wild relatives of crop plants with high salt tolerance. Though the fact that only a small group of higher plants can grow in the saline habitats was recognized many hundred years ago, the name ‘halophyte’ was assigned to such plants by Pallas in the early nineteenth century. Halophytes are plants of physically wet but physiologically dry habitats. Relatively few plant species are halophytes—perhaps only 2% of all plant species. Glenn et al. (1999) have suggested a number as high as 6000 species, whereas the eHALOPH Halophyte Database currently identifies more than 1500 species as salt tolerant, without labelling them as ‘halophyte’. These are highly evolved and specialized organisms with well-adapted morphological, anatomical and physiological characteristics allowing them to proliferate in the soils possessing high salt concentrations (Flowers et al. 1977; Flowers and Colmer 2008). The general physiology of halophytes as reviewed occasionally with salinity tolerance, i.e. growth, osmotic adjustment, ion compartmentation and compatible solutes, salt glands will provide an insight into understanding of the mechanism of salinity tolerance in halophytes. It is likely that the genes that are responsible for the superior salt tolerance in halophytes may serve as a subset of the genes for improvement in crops. Due to their close affinity to the cereal crops, the success of transformation of genes from halophytes in cereal crops is expected to be very pronounced. Improved knowledge of halophytes is of importance to understanding our natural world and to enable the use of some of these fascinating plants in land revegetation, as forages for livestock, and to develop salt-tolerant crops.

This chapter focuses on the suitability of halophytic species to become important components of twenty-first-century farming systems. Halophytic plants become a commercial alternative to ease pressure on the requirement of good quality land for conventional cropping systems and the utilization of land degraded by salinity.

10.1 Halophytes

Notwithstanding the growing interest in plant-based environment-friendly solutions for harnessing the productivity of salt-affected soils and poor-quality waters, Israeli researcher Hugo Boyko pioneered the idea that salty soils and waters could be managed and even improved through the use of certain salt-loving plants called halophytes as early as in the 1960s (Boyko 1966). Halophyte is a collective term to describe the plant species adapted to grow and reproduce in salt-rich environments, making them model species for studying the physiological and genetic bases of salt tolerance and potentially novel crops for generating revenue from deteriorated salty lands otherwise unsuitable for various agricultural uses (Glenn et al. 1999). Although halophytic species have a diverse phylogeny and represent a number of different families, a large majority of them belong to the goosefoot family Chenopodiaceae. In contrast to most of the glycophytic plants which succumb to excessive salinity, halophytes endure exceptionally high levels of root-zone salinity (Flowers and Colmer 2008). However, it is pertinent to mention that considerable genetic differences for salt tolerance are also seen in halophytes: while monocot halophytes grow profusely at relatively moderate salinity (NaCl; ~50 mM), dicot species tolerate nearly double this salinity (~100 mM) without any appreciable reductions in growth. Again, certain dicot halophytes exhibit optimum growth at salinity levels as high as 200 mM. Better adaptability of halophytes to harsh saline conditions is attributed to a set of morphological, anatomical and physiological features, enabling them to live with salinity (Flowers et al. 1977). The fact that growth of some halophytes is even not affected at salt levels above seawater salinity has led to their widespread use for the greening and reclamation of saline soils (Riadh et al. 2010; Flowers et al. 2010; Manousaki and Kalogerakis 2011). For example, saltbush *Atriplex nummularia* accumulates considerable amount of salts (20–40% on dry mass basis) to produce 20–30 Mg biomass ha^{-1} y^{-1}. Another species called seablite (*Suaeda fruticosa*) can remove ~2.5 Mg salt ha^{-1} y^{-1} in a single harvest (Ghnaya et al. 2005).

Based on their ability to maintain growth under saline conditions, Sengbusch (2003) proposed the grouping of halophyte species into the following categories:

(i) *Obligate halophytes*: Also included tidal plant species called ‘true mangroves’, these halophytes grow satisfactorily only when root-zone salinity is consistently high throughout the life cycle. Several species of family Chenopodiaceae belong to this category.

(ii) *Facultative halophytes*: These also include species, designated as ‘mangrove associates’, establish easily on salty soils but do best only when salinity stress becomes mild in the latter stages of growth. Most of the halophytes from plant families Poaceae, Cyperaceae and Brassicaceae and several dicotyledons such as *Aster tripolium*, *Glaux maritima* and *Plantago maritima* are good examples of facultative halophytes.

(iii) *Hydro-halophytes*: As the name suggests, these halophytes are found on wet landscapes and salt marshes along the sea coast.

(iv) *Xerohalophytes*: These ‘succulent halophytes’ grow in dry saline areas and have salt bladders on the leaf surface for secreting the salt.

(v) *Marine phanerogams*: In contrast to the above-mentioned terrestrial halophytes, these are seed-bearing, sea-dwelling species completing their life cycle while remaining completely submerged in seawater.

10.2 Stress-sensing Mechanisms in Plants

Plants employ a suit of stress-sensing mechanisms which act either individually or combinedly to activate the downstream signal transduction pathways:

1. *Physical sensing*: By sensing the mechanical effects of stress at whole plant or cellular level (e.g. shrinkage of the cell membranes).
2. *Biophysical sensing*: By sensing the changes in structure or function of cell enzymes and other biochemical constituents.
3. *Metabolic sensing*: By detecting the by-products synthesized in response to disruption of enzymatic and/or electron transfer reactions, often resulting in overproduction of ROS.
4. *Biochemical sensing*: By sensing the presence of proteins specific to a particular stress (e.g. Ca channels perceive the alterations in cellular temperature and Ca^{2+} homeostasis).
5. *Epigenetic sensing*: By sensing the changes in the structure of DNA and/or RNA molecules but without any alterations in the genetic sequence.

10.3 Effects of Salt Stress

Salt-stressed plants suffer initially from the osmotic stress and subsequently from the specific ion effects. Osmotic stress retards water absorption, cell expansion and lateral bud development and is sensed by the plants shortly after root-zone salinity exceeds the threshold. Subsequent to adjusting osmotically by lowering the water potential to prevent the loss of turgor, most plant species suffer from slow growth at the latter stages. Nutritional imbalance—another deleterious effect of excess

Table 10.1 Salt stress-induced responses in plants

Type of stress	Causes	What happens		Recovery/adaptation
Salinity	Osmotic stress (dehydration)	Reduced water uptake hampers cell elongation and leaf bud development	Cell death	Accumulation of inorganic and organic solutes for osmotic adjustment
	Ion toxicity	Leaf senescence and decreased enzyme activities impair photosynthesis and protein synthesis		Ion homeostasis, extrusion and compartmentation
	Imbalanced ion uptake	Reduced availability of K^+, Mg^{++} and Ca^{++} aggravates nutritional problems		Ion reabsorption

Kumar et al. (2018c)

salinity—further reduces the plant growth. High soil Na^+ and Cl^- levels not only cause direct injury but also decrease the availability of K^+, Mg^{++} and Ca^{++} and NO_3^-, respectively. Accumulation of Na^+ and Cl^- in the plant cells marks the onset of ‘specific ion toxicity’ (Table 10.1). In salt-free normal soils, higher plants maintain 100–200 mM K^+ and 1–10 mM Na^+ in cell cytosol to ensure optimum enzyme activities. Various metabolic activities are disrupted once the cellular salt concentrations exceed the threshold. Excessive accumulation of Na^+ and/or Cl^- ions in the chloroplasts hampers photosynthesis. In comparison to photosynthetic electron transport which is somewhat insensitive to salt stress, both carbon metabolism and photophosphorylation decline resulting in reduced photosynthetic efficiency. Plant leaves containing higher Na^+ show decreased activities of cell organelles and metabolites and chlorosis and necrosis symptoms. Such adverse effects are more pronounced in plants facing both osmotic and salt stresses simultaneously. Elevated Na^+/K^+ ratio in vegetative tissues suppresses enzymatic activities and protein synthesis. Excess Na^+, by replacing Ca^{2+} from the plasma membrane, alters the plasma membrane composition, stability and permeability.

Preceding discussion clearly reflects that excessive accumulation of Na^+ and/or Cl^- ions is one of the major detrimental effects of salinity stress in plants, necessitating focussed research on deciphering the uptake and transport pathways of and cellular compartmentalization mechanisms for these toxic ions. Their entry inside the plant not only reduces the uptake of other essential nutrients but also causes a suit of physiological abnormalities. Various deleterious effects of high Na^+ and Cl^- concentration on cellular systems are shown in Fig. 10.1.

Because plants in saline soils are constantly exposed to the ionic toxicity, their better growth and survival would depend on a great extent how efficiently cellular salt concentrations are maintained below threshold through internal compartmentalization, i.e. sequestration into cell vacuoles. At higher salinity levels, plants’ ability to exclude excess Na^+ weakens gradually such that cellular Na^+ levels keep rising.

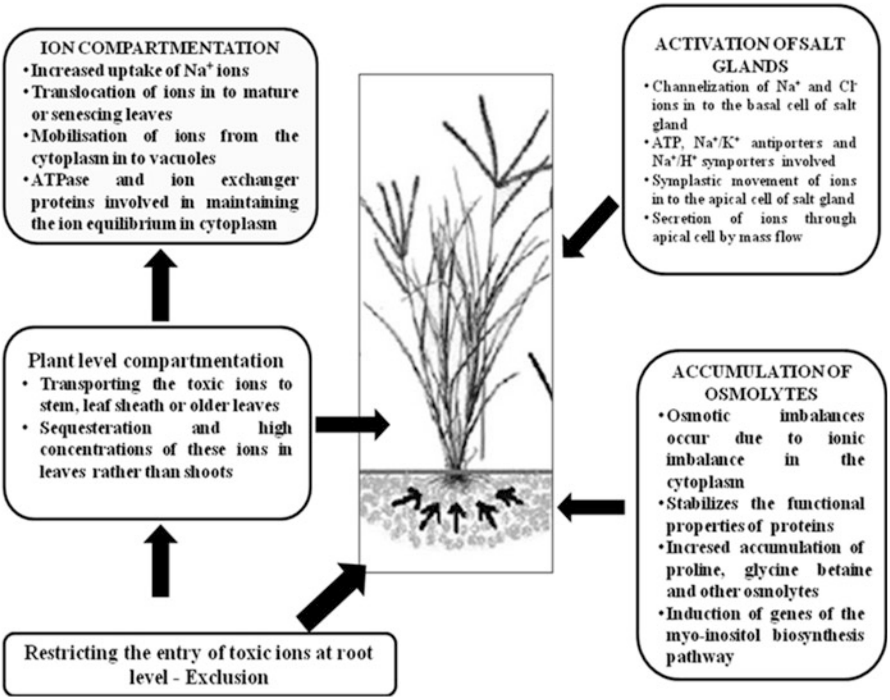

Fig. 10.1 Salt tolerance mechanism in plants

Na^+ ions entering the cell cytoplasm are transported to the vacuole via Na^+/H^+ antiporter system. Major tonoplast proteins regulating vacuolar sequestration of Na^+ belong to vacuolar H^+-ATPases (V-ATPases) and H^+-pyrophosphatases (H^+-PPases). These proteins generate sufficient electrochemical potential for energizing tonoplast membrane and NHX Na^+/H^+ exchangers for Na^+ influx into vacuoles in exchange with H^+. Increased intracellular Na^+ levels also induce Ca^{2+} signalling, activating Na^+ efflux from plant cells via *SOS1*/*SOS2*/*SOS3* pathway.

In the beginning, Na^+-induced Ca^{2+} signalling activates *SOS3*—a calcineurin B-type-like Ca-binding protein with a myristoyl anchor at the *N* terminus. *SOS3* with bound Ca then moves to the plasma membrane and interacts with *SOS2*—a serine/threonine protein kinase. Subsequently, *SOS3/SOS2* complex activates *SOS1*—an ATP-dependent Na^+/H^+ exchanger with 12 transmembrane helices and a long intracellular chain which can be phosphorylated by *SOS2/SOS3* complex. Activation of *SOS1* excludes Na^+ from the plant cells by promoting the exchange of Na^+ with H^+ at the expense of ATP. It also appears that *SOS1* might restrict Na^+ loading into xylem, thus modulating Na^+ levels in the transpiration stream and its eventual translocation from root to shoot. Evidently, upregulation of SOS pathway proteins increases the salt tolerance of plants (Mann et al. 2015).

10.4 Halophytic Species of North-Western India

Different plant species representing over 16 angiosperm plant families and exhibiting halophytic characteristics have been reported from various locations of north-western India (Devi et al. 2016).

A maximum of these halophyte plants belong to the family Chenopodiaceae (e.g. *Atriplex amnicola*, *A. lentiformis*, *A. nummularia*, *Chenopodium album*, *C. ambrosioides*, *C. murale*, *Haloxylon recurvum*, *Salsola baryosma*, *Suaeda fruticosa* and *S. nudiflora*) followed by four each in Mimosaceae (*Acacia nilotica*, *A. ampliceps*, *A. colei* and *Prosopis juliflora*) and Poaceae (*Cynodon dactylon*, *Arundo donax*, *Setaria glauca* and *Saccharum munja*). Other plant families representing one or two plant species include Capparidaceae (*Capparis aphylla*), Portulacaceae (*Portulaca oleracea*), Tamaricaceae (*Tamarix dioica*), Fabaceae (*Sesbania sesban*), Caesalpiniaceae (*Parkinsonia aculeata*), Aizoaceae (*Trianthema portulacastrum*), Compositae (*Xanthium strumarium*), Salvadoraceae (*Salvadora persica*), Asclepiadaceae (*Calotropis procera*), Boraginaceae (*Heliotropium ramosissimum*), Cyperaceae (*Cyperus rotundus*), Solanaceae (*Solanum xanthocarpum* and *Physalis longifolia*) and Amaranthaceae (*Achyranthes aspera and Aerva tomentosa*) (Table 10.2).

10.5 Characteristics of Halophytes (Fig. 10.2)

- Specialized features of halophyte plants enabling them to withstand continual exposure to salinity include thicker and succulent leaves, larger cells, smaller and fewer stomata and well-developed water-storing tissues. In some halophytes (e.g. *Salicornia*), high degree of succulence is attributed to the development of larger cells on the spongy mesophyll and presence of a multilayer palisade tissue.
- Salt-secreting halophytes (i.e., those not accumulating salts) are generally non-succulent.
- Several halophytic species, particularly those belonging to family Chenopodiaceae, withstand high external salt levels by osmotic adjustment, commonly by accumulating Na^+ and Cl^-. In some species, accumulation of organic compounds like glycine betaine and proline also contributes considerably to lowering salt concentrations in the cytoplasm.
- In addition, halophytes also regulate the uptake and transport of Na^+ and Cl^- ions so that their concentration remains within tolerable limit.
- In areas where halophytes predominate naturally, seeds may remain dormant till the onset of rains.
- A deep penetrating root system, up to 5 m deep in species like *Suaeda monoica* and *Atriplex halimus* and up to 20 m deep in others (e.g. *Prosopis farcta* and *Alhagi*), also contributes in increasing tolerance to salinity and associated problems.

Table 10.2 Taxonomical details of species collected from different saline locations

Sr. No.	Family	Species Botanical names	Vernacular name
1.	Capparidaceae	*Capparis aphylla*	Kair
2.	Portulacaceae	*Portulaca oleracea*	Kulfa
3.	Tamaricaceae	*Tamarix dioica*	Morpankhi
4.	Fabaceae	*Sesbania sesban*	Rawasan
5.	Caesalpiniaceae	*Parkinsonia aculeata*	Vilaytikikar
6.	Mimosaceae	*Acacia nilotica*	Kikar
		Acacia ampliceps	
		Acacia colei	
		Prosopis juliflora	
7.	Aizoaceae	*Trianthema portulacastrum*	Santhi
8.	Compositae	*Xanthium strumarium*	Bhangra
9.	Salvadoraceae	*Salvadora persica*	Pilu
10.	Asclepiadaceae	*Calotropis procera*	Ak
11.	Boraginaceae	*Heliotropium ramosissimum*	
12.	Solanaceae	*Solanum xanthocarpum*	Berkateli
		Physalis longifolia	Solanaceae
13.	Amaranthaceae	*Achyranthes aspera*	Puthkunda
		Aerva tomentosa	Dholimundi
14.	Chenopodiaceae	*Salsola baryosma*	Bui
		Chenopodium ambrosioides	Khatua
		Chenopodium murale	Khartua
		Suaeda fruticosa	Bui (Lonia)
		Suaeda nudiflora	
		Chenopodium album	Bathua
		Atriplex nummularia	Stocksii
		Atriplex amnicola	
		Atriplex lentiformis	
		Haloxylon recurvum	
15.	Cyperaceae	*Cyperus rotundus*	Motha
16.	Poaceae	*Cynodon dactylon*	Doob
		Arundo donax	Narhal
		Setaria glauca	Bandarighas
		Saccharum munja	Munj

10.6 Mechanisms in Halophytes to Mitigate the Effect of Salinity

The physiology of salt tolerance in halophytes has intensively been studied (Koca et al. 2007; Da Silva et al. 2008). Halophytes have developed efficient means of osmotic adjustment: accumulation of inorganic salts (mainly NaCl) in the vacuole

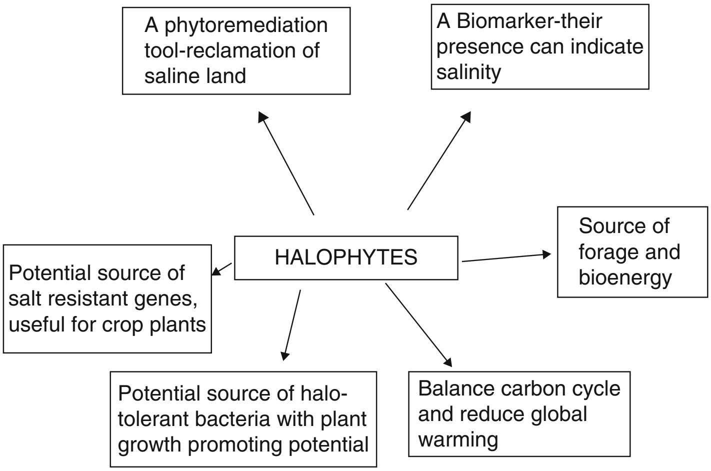

Fig. 10.2 Characteristics of halophytic plants

and of organic solutes in the cytoplasm. Salts absorbed by the halophytes do not inhibit plant growth directly, but indirectly affect various processes like turgor maintenance, photosynthesis and activity of one or another enzyme. Gradual build-up of salts in the old leaves accelerates their senescence and death, limiting the supply of photoassimilates and or hormones to the actively growing tissues (Munns et al. 1995). While Na^+/H^+ antiporters are constitutive in halophytes, they are induced by salt in salt-tolerant glycophytes and mostly absent in salt-sensitive glycophytes. Presumably, large-sized vacuoles in halophytes have such a lipid composition that does not allow leakage of Na^+ back to the cytoplasm (Glenn et al. 1999). For example, in halophyte *Suaeda maritima*, a little over three fourths of the vacuole consists of mesophyll cells (Hajibagheri et al. 1984), making it capable of accumulating higher concentration of salts. Although salt accumulation occurs in nearly all the halophytes, the degree of accumulation is essentially species-specific. It has been shown that several adaptive traits including ion compartmentalization, osmolyte synthesis, succulence, selective uptake and transport of ions, enzyme responses, salt excretion and genetic control come into play in relation to salt tolerance of halophytes (Koyro et al. 2011).

Strategies for adaptation of plants to salt stress avoidance mechanism:

(i) **Exclusion**: The root system of halophytes is equipped with an ultrafiltration mechanism for restricting the radial translocation of salt ions occurring between the soil and xylem. Ions are first transported from the soil solution to the xylem and subsequently from xylem to shoot along with transpiration stream. However, some of the ions are transported via symplastic pathway, bypassing the Casparian strip. Plants possessing efficient salt exclusion capacity succeed in preventing the salt ions from reaching the meristematic regions of actively expanding and photosynthesizing shoots and leaves. Maintenance of a low

Na^+/K^+ ratio facilitates protein synthesis and other metabolic reactions. Some mangrove halophytes showing almost complete salt exclusion include *Rhizophora mucronata*, *Ceriops candolleana*, *Bruguiera gymnorrhiza* and *Kandelia candel*.

(ii) **Excretion**: In addition to salt exclusion, halophytes also actively secrete salt ions—A process called excretion. Because of high concentration in soil solution, Na^+ is passively absorbed to the membrane. In order to maintain low Na^+/K^+ ratio, plants secrete Na^+ back into the soil solution. Certain halophytes like *Tamarix* and *Atriplex* have salt glands in leaves for accumulating the superfluous salt ions. Subsequently, this salt gets crystallized and becomes non-toxic to the plant.

(iii) **Dilution**: Halophytes use one of two strategies, viz. higher uptake of water and rapid growth of tissues for diluting the salts previously accumulated. The dilution mechanism is especially found in succulent halophytes. Such species have a high volume/surface area ratio with rapid growth, leading to the dilution of toxic ions.

(iv) **Compartmentation of ions**: In general, plants tend to lessen the risk of ion toxicity by sequestering Na^+ and Cl^- ions into cell vacuoles and/or in other less sensitive tissues. However, continual compartmentalization into vacuoles cannot always be possible, especially in glycophytes. Under such situations, plants accumulate excessive amounts of Na^+ in the cytosol, albeit with impairments in many cellular functions and processes. Salt ions can be compartmentalized either at organ level where they are retained in the roots and basal stems for reduced translocation to shoots/leaves or at cellular level where salts are sequestered in vacuoles so that their concentrations in cytoplasm remain below toxic level, protecting enzymes in the cytosol.

10.7 Salt Tolerance Mechanism

In contrast to glycophytes, halophytic plants take up Na^+ and Cl^- in large quantities and at a rapid rate, resulting in very high concentrations of these ions in the leaves. Most of the halophytes possess the mechanisms of osmoregulation, ion accumulation and compartmentalization and activation of antioxidant defence system for enduring extremely saline habitats (Fig. 10.3).

Osmoregulation Osmoregulation, also referred to as osmotic compensation or osmotic adjustment, enables the salinized plants to maintain the cell turgor by increasing cell solutes sufficiently for compensating the external osmotic stress. While considerable amount of energy is needed for the synthesis of organic solutes (Marschner 1986), accumulation of inorganic ions in vacuoles can be achieved with far lesser energy (Flowers et al. 1977). As differential contribution of inorganic and organic solutes to osmoregulation has important implications for cellular energy balance, both degree of osmotic adjustment and the type of solutes involved need to be considered for a better understanding of the physiological differences among plants differing in salt tolerance.

- Osmoregulation with inorganic solutes: In most of obligate halophytes, osmoregulation is achieved mainly by the accumulation of inorganic ions from the external medium. The relative contribution of different ions to osmoregulation varies with (I) membrane permeability; (II) transport kinetics, energetic and selectivity; and (III) negative feedback controls regulating membrane transport. Because of different rates of uptake by the plants, ions vary in their role in osmotic adjustment. For example, Cl^- contributes more to osmotic adjustment than SO_4^- because of its relatively rapid uptake. When salinity occurs predominantly due to monovalent cations and divalent anions, cation uptake rate may exceed that of anions and thus differences in their relative contributions to osmoregulation. Imbalance in inorganic cations and anions can further be accentuated by the metabolic assimilation of nitrate and sulphate. Plants also achieve ionic balance by synthesizing and accumulating the organic acids (Fig. 10.3).
- In euhalophytes, accumulation of large amounts of NaCl is the main strategy for adaptation to salinity. These halophytes tolerate excessive levels of salts by increasing succulence, via compartmentation, by secreting salts from the tissues or through a combination of these mechanisms. In several other halophytes, however, increased K^+ uptake plays a major role in osmoregulation. In general, halophytes from Gramineae, Lunaceae and Cyperaceae families show this

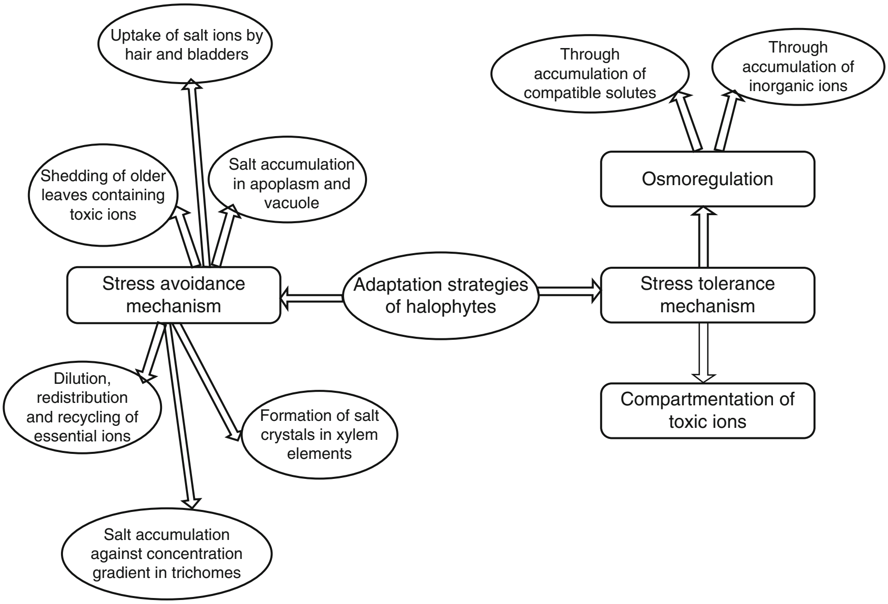

Fig. 10.3 Mechanism of salt avoidance and tolerance in halophytic plants. (Adapted from: Devi et al. (2019))

mechanism: They absorb less Na^+ and preferentially accumulate K^+. Osmoregulation through inorganic solutes is not unique to halophytes though; many glycophytes may also possess this feature. For example, higher salt tolerance in a tomato variety was due to accumulation of Na^+ and Cl^- in the leaves.

- Osmoregulation with organic solutes: Maintenance of a balance between cell vacuole having high salt concentration and the cytoplasm through the synthesis and accumulation of compatible organic solutes plays a critical role in determining the performance of halophytes in salt-affected soils. The term 'compatible solutes' refers to the solutes which are non-toxic or less toxic to metabolic functions than inorganic ions. Major examples include glycine betaine, proline, sucrose and organic acids such as malate and oxalate accumulated in the cell cytoplasm at low external water potentials.
- Greenway and Munns (1980) Suggested that organic solutes play an important role in maintaining osmotic balance between the cytoplasm and vacuole, protecting the cellular components and enzymes from damage. A range of solutes display such protective functions under extreme conditions. Sucrose protected isolated chloroplasts against injury desiccation, and proline increased the solubility of proteins. Osmotic adjustment in the cytoplasm is accomplished mainly by compatible solutes which do not interfere with enzymes and metabolism. These compatible solutes are mostly organic compounds such as the nitrogenous compounds glycine betaine and proline and, in some plants, sugar alcohols, such as sorbitol. In addition, potassium is thought to be maintained in the cytoplasm at a concentration in the order of 4000 mg L^{-1} (100 mM). Glycine betaine (500 mM) is a compatible cytoplasmic solute which alleviated the inhibitory effects of 200 mM NaCl on malic enzyme isolated from barley.
- In contrast to glycine betaine which has a slow rate of degradation, proline is highly labile and disappears rapidly after the stress is relieved and thus acts as a source of nitrogen and energy. Differences in the rate of accumulation and liability suggest that proline could be the major osmolyte in response to a transient stress while glycine betaine possibly to a long-term salt stress. It is due to this reason that unlike proline, glycine betaine does not constitute a potential source of energy and nitrogen.

10.8 Physiological and Biochemical Perspectives

Salicornia bigelovii (dwarf glasswort) grows well at 70 g l^{-1} of dissolved solids and is a promising halophyte for use as a crop. Plants such as barley (*Hordeum vulgare*) and the date palm (*Phoenix dactylifera*) can tolerate about 5 g l^{-1} and can be considered as marginal halophytes (www.nextbigfuture.com). Joshi and Bhoite (1988) studied the ionic relations of *Aeluropus lagopoides* in three salt-affected habitats and found the dominance of Na^+ and Cl^- in leaves, stems and roots and also noted that there was higher accumulation of Cl^- in comparison to Na^+. In *Salvadora* leaf samples, proline and other amino acids increased, and chlorophyll, protein and sugar contents decreased with the increase in salinity of irrigation water (Dagar et al. 2004). Khot and Joshi (2006) reported that under salinity conditions, *Salicornia brachiata* accumulated high levels of amino acids, Na^+ and Cl^- in their green phylloclades. Santhanakrishnan et al. (2014) studied the effect of wastewater containing 2500, 5000, 7500, 10,000, 12,500 and 15,000 ppm of NaCl on physiological and biochemical characters of *Salicornia brachiata* and observed that chlorophyll, carbohydrate, lipid contents and fresh and dry weight showed significant decrease with the increase in salinity and higher accumulation of Na^+, Cl^-, protein and proline. In an experiment on *Salvadora persica* grown on various levels of salinity (0, 250, 500 and 750 mM NaCl) under hydroponic culture condition, it was observed that plant height, leaf area and shoot biomass decreased and leaf succulence increased significantly with increasing salinity after 21 days of salt treatments (Parida et al. 2016). They also observed that reducing sugars, free amino acids and proline content increased, whereas starch content decreased with increasing salinity.

Muchate et al. (2016) obtained no significant change in the activity of antioxidant enzymes (CAT, GR, SOD, APX and GPX) under salinity with higher accumulation of Na^+ in the leaves of *Sesuvium portulacastrum*. In another study on *Sesuvium portulacastrum*, Ramaswamy et al. (2017) reported that shoot/root length and biomass increased to 74% and 94%, respectively, under 5000 ppm of Na-enriched soils. Kumar et al. (2016) have reported the effect of different levels of salinity, sodicity and mixed saline sodic stresses on *Aeluropus lagopoides* (grass halophyte) and *Suaeda nudiflora* (non-grass halophyte) collected from extreme saline sodic Kachchh plains, Bhuj (Gujrat), and observed reductions in the gas exchange attributes of both the halophytes under different saline/sodic levels. These halophytic plant species accumulated the highest Na^+ and Cl^- at ECe 35 dS m^{-1} and also showed increased accumulation of K^+ at ECe 35 dS m^{-1}, with respect to control treatment. Total soluble sugars, protein and proline content were increased with increasing stress environment which showed higher osmotic adaptations in both halophytes. In another study on *Sporobolus marginatus and Urochondra setulosa*, Kumar et al. (2018b) observed increased accumulation of total soluble sugars, proline and epicuticular wax load under different stress conditions of sodicity and salinity and also found that roots accumulated less Na^+ and Cl^- in comparison to their shoots. Na^+ distribution in roots and shoots of salinized plants indicated a tendency for restricted sodium uptake. Devi et al. (2016) studied the comparative phytoremedial potential of *Suaeda nudiflora*, *Suaeda fruticosa*, *Portulaca oleracea*, *Atriplex lentiformis*, *Parkinsonia aculeate* and *Xanthium strumarium* under different levels of salinity and observed that Na^+/K^+ ratio (0.87–2.72), $Na^+/Ca^{2+} + Mg^{2+}$ (0.48–1.54) and Cl^- /SO_4^{2-} (0.94–5.04) ratio increased with increasing salinity levels. In another study, Angrish and Devi (2014) reported the ability of different halophytic species in terms of phyto-accumulation of toxic ions (Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^- and SO_4^{2-}) and observed the trend in the order as *Suaeda nudiflora* > *Suaeda fruticosa* > *Portulaca oleracea* > *Salsola baryosma* > *Atriplex lentiformis* > *Atriplex amnicola* > *Haloxylon recurvum*. Mangalassery et al. (2017)

found the selective absorption of different ions in *Aeluropus* and *Sporobolus* and reported that the uptake of Na^+, K^+ and SO_4^{2-} was reduced in *Aeluropus* with increase in salinity, whereas the uptake of Na^+, K^+ and Cl^- was increased in *Sporobolus*. Kumar et al. (2018a) observed that *Dichanthium annulatum* (grass halophyte) restrict the accumulation of Na^+ in root zone and also found that roots accumulated less Na^+ (0.27%) in comparison to shoots (4.58%) under different levels of salinity, sodicity and mixed stress condition. Nikalje et al. (2018) reported a contrasting pattern of Na^+ and K^+ accumulation in root and leaves of *Sesuvium portulacastrum* under 150 mM and 500 mM NaCl treatment and also found that roots accumulated less Na^+ as compared to leaves. They also reported that the activity of genes particularly *NHX3* (sodium-proton exchanger), *vATPase* (vacuolar ATPase) and *SOS1* (salt overly sensitive1) was upregulated after 6–24 h of salt stress. Lata et al. (2018a) reported that total soluble sugars, glycine betaine, proline, protein content and antioxidant enzyme activities increased with increasing salinity and sodicity stresses in *Urochondra setulosa*. In another study, Lata et al. (2018b) screened *Suaeda nudiflora* (non-grass halophyte, Chenopodiaceae) and *Sporobolus marginatus* (grass halophyte, Poaceae) under different levels of salinity and sodicity and found that protein content increased with increased sodicity/salinity and also found no significant differences in protein profiling under sodic stress.

10.9 Antioxidative Defence Metabolism

Salinity and other abiotic stresses often induce overproduction of reactive oxygen species (ROS), leading to the activation of ROS scavenging system by the plants. ROS are extremely reactive in nature, causing damage to the proteins, lipids, carbohydrates and DNA and ultimately leading to oxidative stress. The antioxidant defence system insulates plants against the oxidative stress. The main ROS (O_2^-, OH^-, H_2O_2) are highly reactive and can oxidize specific amino acids such as histidine, methionine and tryptophan. They weaken the cell membranes by causing lipid peroxidation (Demidchik 2014). Some heavy metals also generate oxidative stress by producing oxyradicals (Mittler 2002). Hydroxyl radical (OH^-) is involved in oxidative stress signalling and programmed cell death (PCD) (Demidchik 2014), and in the activation of the Ca^{2+} and K^+ plasma membrane channel, leading to Ca^{2+} and K^+ efflux as an early response to oxidative stress (Zepeda-Jazo et al. 2011; Rodrigo-Moreno et al. 2013; Demidchik 2014). Regulation of such channels in response to the hydroxyl radical is of considerable importance in halophytes to enable them to regulate cellular Na and K concentrations (Flowers et al. 2010)

Plants have enzymatic and non-enzymatic antioxidant systems to scavenge ROS produced as a result of stress. The induction of antioxidant enzymes including SOD, CAT, GPX, POX, GR and APX is an important protective mechanism to minimize oxidative damage in stress conditions (Qiu et al. 2008; Dazy et al. 2009; Kumari et al. 2010). The non-enzymatic system consists of antioxidants such as glutathione (GSH), ascorbate and α-tocopherol. SOD acts as first line of defence against cellular injury by stresses as it is the major O_2^- scavenger and generates H_2O_2 and O_2

(Grateao et al. 2005). The product of SOD activity (H_2O_2) is still toxic and must be eliminated by conversion to H_2O in subsequent reactions by a number of intracellular enzymes. Among these CAT, APX and GPX are considered the most important enzymes (Noctor and Foyer 1998). As the rate of H_2O_2 radicals increases by the SOD pathway, GPX, APX and CAT pathways are induced, which help in the removal of these deleterious free radicals from the cells. Shackira and Puthur (2017) recently observed higher ROS production as evidenced from increased MDA content under cadmium stress (40 μM) in halophyte *Acanthus ilicifolius* L. and also an increase in the activity of antioxidant enzymes SOD and GPX. SOD is the most effective intracellular metalloenzyme that is ubiquitous in all subcellular compartments prone to ROS-mediated oxidative stress (Gill and Tuteja 2010; Lutts and Lefevre 2015). Zhang et al. (2011) reported in mangrove *Sonneratia apetala* an increase in GPX and SOD activities under heavy metals including Cd, present in wastewater (growing medium). Two- and threefold increase in the GPX activity was recorded in the roots of *B. gymnorrhiza* and *K. candel*, respectively, upon Cd treatment (Zhang et al. 2007). The higher increase in GPX activity points towards a more important role than SOD, CAT and APX, in the detoxification mechanism of *A. ilicifolius* under Cd stress and also in other halophytic plants including *Kosteletzkya virginica* (Rui-Ming et al. 2013), *Salicornia brachiata* (Sharma et al. 2010; Wang et al. 2014) and *Spartina alterniflora* (Chai et al. 2013). Wu et al. (2013) observed that CAT gene expression levels significantly increased in response to Zn, Pb or the combination of both metals in shoots of *Suaeda salsa*, while activities of the antioxidant enzymes SOD, glutathione peroxidase (GPX) and catalase (CAT) increased in response to Zn and Zn + Pb.

As far as non-enzymatic antioxidants are concerned, ascorbate is a ubiquitous soluble antioxidant in plant cells, which can directly scavenge ROS and act as a reducing substrate for APX and GPXs to detoxify H_2O_2 (Mittler 2002). Shackira and Puthur (2017) reported in *A. ilicifolius* under Cd treatment that from 3 days onwards, ascorbate content exhibited an increasing trend over the control plants throughout the treatment period in the root tissue. Maximum accumulation of ascorbate content was recorded at 9 days of treatment, i.e. 21-fold increase over the control plants and reduced significantly to 15-fold on 15 days after Cd treatment. This observed significant increase in the ascorbate content may counteract or neutralize the harmful effects of ROS produced in the root cells as have been reported in halophyte, *Kosteletzkya virginica* (Rui-Ming et al. 2013).

Glutathione (GSH) also acts as ROS scavenger by chelating metal ions (Yadav 2010). Although salinity induces oxidative stress in glycophytic species, it has been reported to reduce Cd-induced oxidative damages in some wetland halophytes. An increase in α-tocopherol and in ascorbic acid in response to NaCl was reported to reduce oxidative damage resulting from Cd stress (Han et al. 2013). Carotenoids serve as antioxidants against free radicals and photochemical damage (Sengar et al. 2008). Carotenoids are able to quench the oxidizing species and triplet state of the chlorophyll and other excited molecules of photosynthetic pigment bed, which are seriously involved in disrupting metabolism through oxidative damage to cellular components (Candan and Tarhan 2003). The carotenoids decreased under heavy metal stress in halophytic plants (Mesnoua et al. 2016). However effect on carotenoid content was less than chlorophyll (Chl) content. Metals can enhance or reduce carotenoid production depending on metal types (Fargasova 1998; Singh and Tewari 2003).

Heavy metal and salinity both induce oxidative stress individually and in combination, but in halophytic plant salinity stress-induced oxidative metabolism helps in coping with heavy metal stress by reducing the toxic effects. In *Sesuvium portulacastrum*, in vivo tissue fluorescence imaging confirmed that NaCl drastically reduced the concentration of H_2O_2 in both leaves and stems of Cd-treated plants (Wali et al. 2014). Han et al. (2012) also observed that salinity protects halophytic species *K. virginica* against Cd stress via an improved management of oxidative stress and hormonal status and showed the combined treatment of Cd and NaCl have a synergistic negative effect. Hasna et al. (2013) observed that salinity, drought and cadmium pretreatments to halophyte *Cakile maritima* result in lower levels of hydrogen peroxide and malondialdehyde, an indicator of lipid peroxidation, under salt treatment (100–800 mM NaCl), particularly at high NaCl concentrations, and showed the subsequent tolerance response.

10.10 Molecular Responses

Halophytes possess many features for regulating the development and functions of cells in salt-rich soils. As mentioned previously, salt stress regulation also involves complex gene networks and proteins. A number of genes conferring salt tolerance to halophytes have been identified (Table 10.3) which includes cation/proton antiporters (SOS1, SOS2, SOS3) on the plasma membrane; P5CS and NHX1 on vacuolar membrane and plasma membrane and vacuolar H^+-ATPases and potassium transporters. Salt stress alters the expression of the genes involved in maintaining intracellular ionic homeostasis (Shabala et al. 2015; Joshi et al. 2015; Himabindu et al. 2016).

An important way of salt tolerance involves maintenance of K^+ ion with reduction in excess Na^+ ion in the cytosol. On the plasma membrane, SOS1 causes reduction of excess Na^+ from cells, or in vacuolar membrane NHX causes sequestration of Na^+ into vacuoles (Bassil et al. 2011; Himabindu et al. 2016). These antiporters of vacuoles are also involved in the sequestering of K^+ (Barragán et al. 2012). Along with the salt tolerance, these antiporters have also basic functions such as pH maintenance and cell expansion, membrane trafficking, ion homeostasis and stomatal conductance (Himabindu et al. 2016; Reguera et al. 2013).

High saline condition causes the enhancement in the production of Ca^{2+} in cytosol which indicates the salt stress in plants. The enhanced Ca^{2+} leads to restoration of membrane voltage and activation of further plasma membrane H^+-ATPases and leads to ROS production. The production of Ca^{2+} and ROS causes release of abscisic acid which in turn starts transcription process (Himabindu et al. 2016). The elevated Ca^{2+} ion binds with SOS3/CBL4 (calcineurin B-like 4) which activates SOS2/CIPK24 by binding to them (Zhu 2003; Guo et al. 2004). SOS2 and SOS3 complex phosphorylates the SOS1which results into Na^+ efflux (Martínez-Atienza et

Table 10.3 Genes of halophytic origin that enhance salt tolerance in glycophytic plants

Halophytes	Genes	Description	Recipient plants	References
Aeluropus littoralis	AlNHX1	Vacuolar Na^+/H^+ antiporter	*Nicotiana tabacum*	Zhang et al. (2008)
Atriplex centralasiatica	AcBADH	Synthesis of glycine betaine	*Nicotiana tabacum*	Yin et al. (2002)
Atriplex gmelinii	AgNHX1	Vacuolar Na^+/H^+ antiporter	*Oryza sativa*	Ohta et al. (2002)
Atriplex hortensis	AhBADH	Synthesis of glycine betaine	*Tomato*	Jia et al. (2002)
Atriplex hortensis	AhProT1	Proline transport	*Arabidopsis*	Shen et al. (2002)
Atriplex nummularia	AmCMO	Enhanced glycine betaine synthesis	*Nicotiana tabacum*	Tabuchi et al. (2005)
Avicennia marina	AmMDHAR	Ascorbate regeneration and ROS scavenging	*Nicotiana tabacum*	Kavitha et al. (2010)
Halostachys caspica	HcNHX1	Vacuolar Na^+/H^+ antiporter	*Arabidopsis*	Guan et al. (2011)
Halostachys caspica	V-ATPase	Vacuolar-H^+-pyrophosphatase	*Arabidopsis*	Hu et al. (2012)
Kalidium foliatum	V-ATPase	Vacuolar-H^+-pyrophosphatase	*Arabidopsis*	Yao et al. (2012)
Salicornia brachiata	SbASR1	Abscisic acid stress ripening-1	*Arachis hypogea*	Tiwari et al. (2015)
Salicornia brachiata	SbGSTU	TAU class glutathione transferases	*Nicotiana tabacum*	Jha et al. (2013)
Salicornia brachiata	SbMT-2	Metallothionein: ROS scavenger	*Nicotiana tabacum*	Chaturvedi et al. (2014)
Salicornia brachiata	SbNHX1	Vacuolar Na^+/H^+ antiporter	*Jatropha curcas*	Joshi et al. (2013)
Salicornia brachiata	SbNHX1	Vacuolar Na^+/H^+ antiporter	*Ricinus communis*	Patel et al. (2015)
Salicornia brachiata	SbNHX1	Vacuolar Na^+/H^+ antiporter	*Cuminum cyminum*	Pandey et al. (2016)
Salicornia brachiata	SbpAPX	Peroxisomal ascorbate peroxidase	*Nicotiana tabacum*	Singh et al. (2014a)
Salicornia brachiata	SbpAPX	Peroxisomal ascorbate peroxidase	*Arachis hypogea*	Singh et al. (2014b)
Salicornia brachiata	SbSDR1	Salt- and drought-responsive gene	*Nicotiana tabacum*	Singh et al. (2016)
Salicornia brachiata	SbSRP	Salt-responsive protein-encoding gene	*Nicotiana tabacum*	Udawat et al. (2017)
Salicornia brachiata	SbUSP	Cytosolic universal stress protein	*Nicotiana tabacum*	Udawat et al. (2016)
Salicornia europaea	SeCMO	Enhanced glycine betaine synthesis	*Nicotiana tabacum*	Wu et al. (2010)
Salsola soda	SsNHX1	Vacuolar Na^+/H^+ antiporter	*Alfalfa*	Li et al. (2011)

al. 2007; Quintero et al. 2011). The function of SOS1 is not only restricted to remove Na^+ from cytosol but also to transport Na^+ from the root to shoot (Shi et al. 2002; Himabindu et al. 2016). The salt-accumulating halophyte, *Salicornia dolichostachya*, expresses high level of SOS1 expression as compared to *Salicornia oleracea* which is glycophyte relative of *S. dolichostachya* (Bose et al. 2014). For salt tolerance studies, K/Na ratio is also regarded as a good indicator besides salt-tolerant genes. The K^+/Na^+ ratio decreases in sensitive plants with higher salt concentration, while it increases significantly in the case of salt-tolerant plants (Kumar et al. 2009; Chakraborty et al. 2012; Kumar et al. 2017).

Salinity tolerance mechanism at molecular level is being revealed due to advancement in the functional genomics and proteomics. With the help of advanced techniques such as next-generation sequencing (NGS), the whole genome of several plants has been sequenced. The whole genome provides a detailed map of sequences of genes. Goyal et al. (2016) studied the transcriptome profile of wheat (salt-tolerant) under salt stress with the help of NGS and found that in response to salt stress, some transcripts were differentially expressed which have stress tolerance function such as SOS1, sodium-calcium exchanger, sodium-hydrogen exchanger, salt-responsive protein, CBL-interacting protein kinase family, calcineurin B-like protein, salt-induced protein, universal stress protein, stress protein, signal transduction (Ca^{2+} calmodulin-dependent protein kinase and calmodulin), inorganic ion transport (Na+/H+ antiporter, transmembrane protein, plasma membrane H + -ATPase, vacuolar proton-inorganic pyrophosphatase) and energy production and conversion (ATP synthase beta subunit, ATP synthase subunit d, ATP synthase delta subunit, ATP citrate synthase, ATP binding protein, vacuolar ATP synthase subunit b, vacuolar ATPase b subunit, vacuolar-type H+ ATPase, vacuolar proton ATPase b subunit). In the salt-tolerant variety of *Brassica juncea*, the transcriptome profiling showed that during salt stress, genes regulated are associated with various metabolic processes such as proline biosynthesis (P5CS), calcium signalling, sulphur assimilation (ATPS and APR) and ROS detoxification (glutathione peroxidase, superoxide dismutase, dehydro-ascorbate reductase) (Sharma et al. 2015).

In a plant cell, the metabolism is consisting of several complex biochemical pathways which remain interconnected during intracellular homeostasis. To understand these biochemical pathways and to develop the salt-tolerant plants, a slight modification is necessary in the pathway. At high salt concentration, the Gly I gene of glyoxylate pathway isolated from the *Brassica* is overexpressed in the transgenic tobacco plant (Veena et al. 1999). It has been established that both Gly I expression and various salt concentrations are correlated. Similarly under the control of promoter 35CaMV, higher expression of several halophytic genes has been observed in a number of glycophytic recipients (Mishra and Tanna 2017). Despite the progress in salt tolerance mechanism, it is opined that some adaptive response of halophytes can be a better option in comparison to *Arabidopsis*. Halophytes have evolved some exclusive mechanism to cope with the salt stress that is absent in the glycophytes (Vera-Estrella et al. 2005).

Besides the genomic analysis, the whole protein profiling is also being analysed to identify proteins which may be an important part of salt tolerance. Various proteins that are identified during salt stress by proteomic approach are involved in the oxidative stress tolerance, chaperone activities, cytoskeleton remodelling, ATP production, glycine betaine synthesis, cyanide detoxification and photosynthesis. Krishnamurthi et al. (2017) reported the proteins that are responsive to long-term salt treatment in the halophyte *Suaeda maritima* and observed that *S. maritime* can grow in salt concentration up to 200 mM NaCl by upregulating the specific proteins that are included in the pathways related to protein folding and assembly, protein transport, vesicle trafficking, chromosome segregation, cell maintenance and heme/iron binding. The salt stress-responsive proteins mainly identified were SCC3, CYP71A8 and RAB2B. Similarly Veeranagamallaiah et al. (2008) identified the salt stress-responsive proteins in *Halogeton glomeratus* by proteomic approach that are involved in the various pathways such as stress tolerance, photosynthesis, energy and carbohydrate metabolism and defence response. Kumar Swami et al. (2011) studied the proteome of *Sorghum bicolor* leaves under salt stress. They exposed the leaves of sorghum at 200 mM NaCl for 96 h in hydroponic culture and identified the 21 proteins having 1.5-fold altered expression. Most of the identified proteins are found to be belonging to inorganic ion transport, signal transduction mechanisms and metabolism. Under stress condition, overexpression of l-ascorbate peroxidase and glutathione-S-transferases was found which are key reactive oxygen species scavenging enzymes (Kumar Swami et al. 2011).

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Characterization and Problems of Saline/Sodic Vertisols and Their Management Options

11

R. N. Katkar, V. K. Kharche, and N. M. Konde

Abstract

Soil degradation resulting from salinity, sodicity, or a combination of both is a major impediment to optimal utilization of soils in the world. It is a prime threat to land resources, resulting in large economic and associated social consequences. The relative significance of soluble salts depends on natural drainage conditions, soil properties, groundwater quality, irrigation water quality, and management practices. Saline–sodic Vertisols and their intergrades occur in different parts of the world. The majority of these soils occur in lower piedmont plains or valleys. They are mainly derived from the basaltic alluvium and have a clay texture with smectitic clay with a high swell–shrink potential, very low hydraulic conductivity, and imperfect drainage. The productivity of these soils is limited. Taxonomically, these salty soils are classified as Sodic Haplusterts and Sodic Calciusterts. There is an increase in pH in subsoil associated with an increase in the exchangeable sodium percentage (ESP) toward lower horizons. These soils have high concentrations of neutral salts and sodium in the exchange complex. The very high clay content of these soils can be attributed to their formation from basaltic parent material. These soils do not show any salt efflorescence on the surface. Initiation of alkalinization is operative in these soils in subsurface layers as a consequence of salt accumulation and its progress in an upward direction along with capillary rise of soil solution during dry periods. The soils are strongly to moderately alkaline with an ESP of 5–26. The soils are reported to be calcareous in nature with a tendency toward an increase in calcium carbonate with depth.

The saline/sodic Vertisols in the Purna River valley have a higher clay content of smectite at the subsurface and are prone to severe problems of drainage. These soils pose serious problems owing to high exchangeable sodium, poor physical condition, and nutrient deficiency. The problems of these soils are native sodicity,

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poor hydraulic conductivity, high calcium carbonate, compact and dense subsoil, incomplete leaching of salts due to poor drainage, and high swell–shrink potential, resulting in water stagnation in the kharif season and wide cracks in the dry season. Soil chemical degradation in terms of increases in ESP and the exchangeable magnesium percentage (EMP) in saline–sodic Vertisols adversely affects hydraulic and other properties important for crop growth. Clay dispersion leads to destabilization of the soil structure and breaking of the soil capillary network, ultimately affecting the water transmission characteristics of the soil.

The decadal change in soil degradation in the Purna valley shows that there has been an increase in pH along with the ESP of the soils over a period of time under the prevailing climate. The soil degradation in the Vertisols of the Purna valley demonstrates that despite low levels of sodicity, the soils have low hydraulic conductivity due to large amounts of smectite clay and high exchangeable sodium in the subsoil. Management options are available for amendment and sustainable productivity of salt-affected swell–shrink soils. The use of amendments (gypsum), land configuration, tillage, and improvements in drainage need to be instituted for amelioration. Innovative approaches include crop residue incorporation, green manuring with dhaincha and sunhemp, and application of organic manure, compost, and spent-wash press-mud compost. Integration of chemical amendments and organic conditioner, along with bio-inoculants, has been found to be beneficial in improving the air–water relationship in sodic soils. Distribution of gypsum in a powdered form before sowing of crops, and mixing of it into surface soil, are recommended for increasing the productivity of cotton, sorghum, and green gram, besides improving the physical and chemical characteristics of sodic soils in the Purna valley.

Keywords
Vertisols · Sodicity · Salinity · ESP · Smectitic clay · Hydraulic conductivity · Amendments · Land configuration · Organic manure

11.1 Introduction

The salt content in the root-zone determines whether soil is normal or salt-affected. When excessive concentrations of soluble salts occur in the soil, plant growth is adversely affected. Soil degradation resulting from salinity, sodicity, or a combination of both is a major impediment to optimal utilization of soils. Salt-affected soils exist mostly in arid and semiarid climates, in many countries in the world. Salinity and sodicity are prime threats to land resources, resulting in huge economic and associated social consequences. Agricultural production in arid and semiarid regions is limited by salinity, sodicity, poor water resources, limited rainfall, and loss in soil fertility, which may be constrained to a localized area or sometimes extends over the whole of the basin. The relative significance of each source in contributing soluble salts depends on the natural drainage conditions, soil properties, groundwater quality, irrigation water quality, and management practices. In 2008, it was estimated by the Food and Agriculture Organization of the United Nations (FAO) that more than 800 million hectares (Mha) of land worldwide were salt-affected (FAO 2008), including saline, saline–sodic, and sodic soils. In India, an area of 6.74 Mha suffers from salt accumulation, out of which 3.78 Mha are sodic soils, while 2.96 Mha are saline soils (Mandal et al. 2010).

11.2 Characterization of Saline/Sodic Black Soils

Vertisols and their intergrades (black soils) occur in different parts of the world. In India, these soils occupy an area of 72.9 million hectares, 35.5% of which are in the state of Maharashtra (Murthy et al. 1982). The majority of these soils occur in lower piedmont plains or valleys and in microdepressions that have developed in the alluvium of weathered Deccan basalt (Pal and Deshpande 1987). These soils are mainly derived from the basaltic alluvium and have a clay texture with smectitic clay mineralogy. It has a high swell–shrink potential, slow permeability with very low hydraulic conductivity, and imperfect to poor drainage conditions. Taxonomically, these salt-affected soils are classified as Sodic Haplusterts and Sodic Calciusterts (Padole et al. 1998a, b). The smectitic clay in black soils in combination with high exchangeable sodium results in a high degree of shrink–swell potential, which causes problems of internal drainage. As an effect of climate change, the rainfall has been observed to gradually decrease over time in this area, and rainy days are drastically reduced with prolonged dry spells coupled with increases in temperature. These changes are causing further increases in soil degradation, and there has been an increase in pH in the subsoil, associated with an increase in exchangeable sodium percentage (ESP) toward lower horizons and a concomitant decrease in the exchangeable Ca/Mg ratio (Kharche et al. 2012).

Australian workers, who attach great importance to deterioration of the physical condition of the soil and its harmful effect on plant growth, consider that the ESP is too high to differentiate sodic soils from nonsodic soils in the case of swell–shrink heavy clay soils. Northcote and Skene (1972) proposed an ESP value of 6 as a threshold value for acute impairment of the physical condition. Kharche and Pharande (2010) observed that even with a comparatively lower ESP in association with high clay content of a smectitic nature, these soils show problems in drainage. They indicated the necessity of lowering the ESP threshold value in black swell–shrink soils for categorizing them as sodic, mainly because the sodification problem in these soils is further aggravated by the high clay content, causing the soils to have inherently slow permeability. Sharma et al. (1997) reported that an ESP value of 5 or 6 in Vertisols could cause considerable deterioration in the physical properties of the soil.

The problems of salinity and sodicity in these areas are becoming more serious and are a matter of concern because of the alarming increases in the area. In India, chemical degradation occurs by salinization and alkalinization, and the problem is increasing at an alarming rate (Suri 2007). Saline–sodic soils have high concentrations of neutral salts and appreciable sodium in the exchange complex. In these soils, both free salts and exchangeable Na^+ are present in excess amounts. These soils differ in terms of their chemical characteristics, as well as their physical and biological properties.

11.2.1 Primary Salinization

Black soils are mainly confined to river valleys, one of which is the Purna valley, covering parts of the Amravati, Akola, and Buldhana districts in the Vidarbha region of Maharashtra (Fig. 11.1). This valley is an oval-shaped basin drained by the Purna River system. Even though the Purna River flows throughout the year, the soils along both banks have been reported as being salt-affected (Adyalkar 1963). The very high clay content of these soils can be attributed to their formation from basaltic parent material (Pal and Deshpande 1987) (Table 11.1). Earlier work carried out in the area (Magar 1990; Nimkar et al. 1992; Kadu et al. 1993) indicated that many soils in this valley are non-saline with an electrical conductivity of saturated paste extract (ECe) of less than 2 dS m^{-1} and an ESP value of less than 15. However, these soils have not been categorized in an appropriate class because they show deterioration at ESP values much lower than 15. These soils do not show any salt efflorescence on the surface (Pal 2004).

An increase in ESP with depth is a general observation in black soils in the semiarid region of peninsular India (Nimkar et al. 1992). Initiation of alkalinization is operative in these soils in subsurface layers as a consequence of salt accumulation and its progress in an upward direction along with capillary rise of soil solution

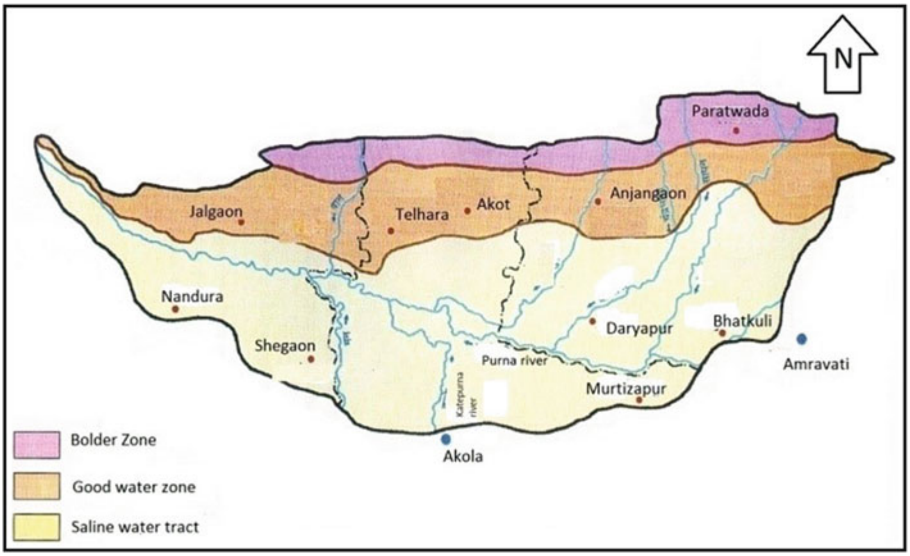

Fig. 11.1 Purna River valley tract

Table 11.1 Ranges of sand, silt, and clay in soil profiles in different villages

Village	Sand (%)	Silt (%)	Clay (%)
Paral	3.50–6.80	20.00–26.40	68.00–74.00
Dapura	4.60–7.20	20.10–24.31	68.50–73.50
Ner	3.00–6.00	24.00–26.80	66.75–73.00
Patsul	5.25–7.60	22.40–25.40	68.00–71.75
Hingna Tamaswadi	2.45–4.25	24.00–26.50	69.25–73.50
Ugwa	2.60–4.60	23.00–26.50	69.25–73.50
Nawed	4.75–8.75	22.00–24.50	67.20–71.75
Kholapur	5.35–8.75	22.00–25.20	68.50–71.75
Overall range	2.45–8.75	20.00–26.80	66.75–74.00

during dry periods. Further, Balpande et al. (1996), in their studies, pointed out that the development of sodicity in soils in the southwestern part of the valley can be attributed to the semiarid climatic conditions, which have induced a pedogenic process of calcium carbonate, resulting in increases in both the sodium adsorption ratio (SAR) and ESP with the pedon depth.

Studies on polygenetic Vertisols in this valley by Pal et al. (2001) revealed that the soils in the southwestern part are strongly alkaline with ESP values of 5–26 and those in the northeastern part are moderately alkaline with ESP values of less than 5. The soils contain both pedogenic and nonpedogenic calcium carbonate. The lack of soil water in the soils in the southwestern area is thought to be the reason for the weak swelling of smectite, larger amounts of pedogenic carbonate, and cracks cutting through the slickenside zone.

The soils are reported to be calcareous in nature, with a tendency for calcium carbonate to increase with depth. This may be due to the semiarid climatic conditions, where the leaching of bicarbonates during the rainy season from the upper soil horizons and their subsequent precipitation trigger development of sodicity in subsoils of the black soils. The precipitation of bicarbonates in the subsoil indicates operative alkalinization under semiarid conditions. The subsoil sodicity also leads to a decrease in the mean weight diameter.

11.2.2 Secondary Salinization

The most predominantly occurring black swell–shrink soils in the canal command areas of Maharashtra pose severe problems of salinity and sodicity due to indiscriminate use of irrigation water coupled with monocropping of crops such as sugarcane and the increasing aridity of the climate. The problem is further aggravated by the very high clay content of the soils, with slow permeability (Fig. 11.2) and restricted drainage causing impairment in soil quality and serious reductions in crop yields.

The soils of the Mula canal command area in the Ahmednagar district, which were normal before the introduction of the canal (Somavanshi and Patil 1986), are now suffering from degradation due to salinity and sodicity (Durgude 1999; Kharche et al.

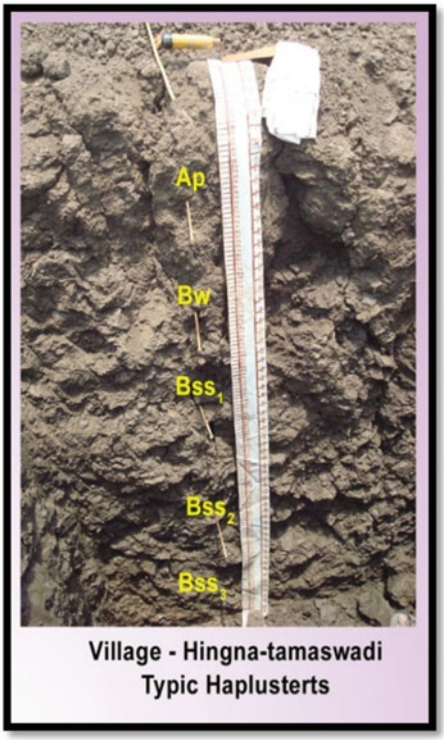

Fig. 11.2 Profile of Vertisols in the Purna River valley

2004). Researchers (Kharche and Pharande 2010) have documented irrigation-induced soil degradation causing serious soil quality deterioration in the Mula command area in Maharashtra, which warrants immediate attention for their reclamation and management.

Irrigation-induced sodicity of Vertisols in the Mula command area in the Ahmednagar district of Maharashtra was studied by Kharche et al. (2004), who concluded that the severity of salinity and sodicity in these soils is further aggravated by the semiarid climate, indiscriminate use of irrigation water, and restricted drainage. The soil reaction was moderately to strongly alkaline with variable pH values in different horizons. The soils were calcareous with high $CaCO_3$ (9.5–16.2%). A high pH value of more than 9.0 was recorded in some soil horizons. The ECe was more than 4 dS m^{-1} (4.84–13.89 dS m^{-1}), and the ESP was high through different horizons (14.3–23.1) and showed a slight increase with increasing depth.

11.3 Problems

The saline–sodic Vertisols in the Purna River valley have a higher clay content of smectite at the subsurface and are prone to severe problems of drainage during the rainy season. The soils in the Purna valley basin are very deep with a high clay content (Table 11.1). The inherently slow permeability of these soils—owing to the smectitic nature of the soils coupled with the plain topography and prevailing semiarid conditions—make these soils vulnerable to salinity and sodicity hazards. These soils pose serious problems owing to a high exchangeable sodium content, poor physical condition, and nutrient deficiency. The major problems of these soils are native sodicity, poor hydraulic conductivity, compact and dense subsoil, incomplete leaching of salts due to severe drainage impairment, and a high swell–shrink potential, resulting in water stagnation in the *kharif* (rainy season) season and wide cracks in the winter season (Balpande et al. 1996; Sagare et al. 2000).

The hydraulic conductivity (0.06–7.3 mm h^{-1}) of the black soils in the Purna valley was studied by Magar (1990) and was found to have a significant negative correlation with the exchangeable magnesium percentage (EMP). A considerable reduction in hydraulic conductivity with depth was observed in deep black soils in this region by Kadu et al. (1993) and Kadam et al. (2013). The coefficient of linear extensibility (COLE) was found to range from 0.18 to 0.28 cm cm^{-1}, indicating high swell–shrink activities in these soils due to the predominance of smectitic clay (Balpande et al. 1996). On the basis of categorization according to the COLE value, these soils have a very high shrink–swell potential (Nayak et al. 2006). The soils show poor internal drainage even at ESP values much lower than 15 (Kadam et al. 2013). Pal et al. (2012) reported that these Vertisols in dry climates have poor drainage, but they show no salt efflorescence on the soil surface as evidence of the threat of soil sodicity.

Pal et al. (2012) also reported that the lower hydraulic conductivity of these soils is related to an ESP value of more than 5 and the exchangeable Ca/Mg ratio. Padole et al. (1998a, b) studied the bulk density of these soils (1.28–1.88 Mg m^{-3}) and reported typically low hydraulic conductivity (5.2–1.7 mm h^{-1}) and a high cation exchange capacity (CEC) (more than 42.3 cmol (p^+) kg^{-1}). The pH, ECe, and ESP values of these soils ranged between 7.3 and 9.6, between 0.90 and 5.74 dS m^{-1}, and between 2.57 and 33.78, respectively. These authors further reported that the hydraulic conductivity of these soils is adversely affected by soil attributes such as the clay and smectite content, bulk density, ESP, and SAR. Kadu et al. (2003) reported that these soils were impoverished with respect to organic carbon, and calcium was a dominant exchangeable cation. In general, exchangeable Ca decreases with depth, while exchangeable Mg increases. Kadam (2011), in his studies on the decadal change in soil degradation in the Purna valley, observed that there has been an increase in the pH along with the ESP of these soils over a period of time under the prevailing climate. Kharche et al. (2012) ascertained the soil degradation in the Vertisols of the Purna valley and pointed out that despite low levels of sodicity (ESP 3.3–11.1), the soils had severe drainage problems due to low hydraulic conductivity. Similarly, it was noted that a large amount of smectite clay leads to an increase in bulk density and thus results in a hard and compact soil structure. The soil pH ranged from 7.0 to 9.12 and the ECe ranged from 0.42 to 2.74 dS m^{-1} (Table 11.2), being increased in the subsoil.

Varade et al. (1985) reported that about 10% of the irrigable Vertisol area in each irrigation project is affected by salt and waterlogging problems. Salt-affected Vertisols have been reported to have saline, saline–sodic, and sodic characteristics. The main cause of salt problems in Vertisols reportedly include unscientific

Table 11.2 Ranges of pH, electrical conductivity (*ECe*), and exchangeable sodium percentage (*ESP*) in soil profiles in different villages

Village	pH	ECe	ESP
Paral	8.0–8.9	1.6–2.74	4.7–5.2
Dapura	8.7–9.12	0.9–2.0	5.0–5.3
Ner	7.7–8.5	0.54–1.14	4.3–6.5
Patsul	7.6–8.3	0.6–1.11	4.3–5.4
Hingna Tamaswadi	7.9–8.8	0.42–0.7	3.9–5.6
Ugwa	8.3–8.6	0.8–1.15	3.3–5.8
Nawed	7.0–8.9	0.67–1.49	4.4–11.1
Kholapur	8.4–8.5	0.88–1.21	4.1–6.1
Overall range	7.0–9.12	0.42–2.74	3.3–11.1

irrigation, the topographical situation, aridity in climate, and groundwater rise due to canal seepage and poor drainability. Dongare (2010) assessed land degradation in the Godavari command area and reported greater severity of degradation due to salinity–sodicity hazards in the lowland compared with the upland. The serious decline in hydraulic conductivity is caused by a very high clay content of a smectitic nature coupled with a low Ca/Mg ratio and high exchangeable sodium and magnesium.

11.4 Management Options for Salt-affected Soils

Various management options are available for amendment and sustainable productivity of salt-affected swell–shrink soils, such as use of amendments, land configuration, tillage, and drainage.

11.4.1 Conventional and Innovative Approaches

The management of salt-affected Vertisols with subsurface drainage and crop residue incorporation was studied by Bharambe et al. (2001) in a soybean–wheat cropping system on sodic Vertisols. The soil reaction and electrical conductivity decreased from 8.26 to 8.20 and from 2.45 to 2.25 dS m^{-1}, respectively, while the organic carbon content increased from an initial value of 6.4 to 7.3 g kg^{-1} with crop residue application, with the highest values being seen with use of green manuring with dhaincha (*Sesbania aculeata*). The physical properties were improved and the salinity and sodicity of the soil were reduced considerably below the critical limits for salinity hazards with incorporation of crop residue such as sugarcane trash (5 Mg ha^{-1}) or green manuring with dhaincha over a period of 4 years. Studies on the effects of land configuration and gypsum levels on the dynamics of soil properties and productivity of cotton grown in sodic Vertisol revealed that the greatest reductions in pH, ECe, saturated paste extract–derived SAR (SARe), and ESP values were noted with incorporation of 100% of the gypsum requirement

(100% GR) (Sagare et al. 2001a, b). The interaction effects between land configuration (opening of a furrow after two rows of cotton) and gypsum levels in reducing the ECe, ESP, and SARe were significant. A significant increase in the hydraulic conductivity of sodic Vertisol was observed with use of gypsum @ 100% GR in comparison with gypsum @ 25% GR.

Application of amendments to sodic black soils of the Purna valley were made on the basis of an increase in the crop yield and soil improvement (Sagare et al. 2000). Application of gypsum 2.5 Mg ha^{-1} (50% GR) in a powdered form before sowing of the crop and mixing it with the surface soil is recommended for increasing the productivity of cotton, sorghum, and green gram, besides improving the physical and chemical characteristics of sodic soils of the Purna valley. For improving the characteristics of soil and sustaining the yields of green gram–safflower on sodic Vertisols of the Purna valley, it is recommended to incorporate crop stubble (2 Mg ha^{-1}) plus phosphate-solubilizing bacteria (PSB) (10 kg ha^{-1}) along with 50% of the recommended doses of fertilizers.

11.4.2 Soil Amendments: Constraints and Alternative Sources

Gypsum, which has been widely used as an amendment in these soils, is also becoming scarce and needs to be supplemented with alternative amendments. Spent-wash press-mud compost (SWPMC), obtained from sugar factories in these areas, is a locally available and inexpensive potential alternative amendment. It was used for reclamation, in conjunction with gypsum, by Kharche et al. (2010), who reported that application of gypsum @ 25% GR along with SWPMC 10 Mg ha^{-1} significantly reduced the soil pH from 8.65 to 8.14, the ECe from 2.93 to 2.30 dS m^{-1}, and the ESP from 18 to 11.4. Integrated use of amendments was found to be beneficial for improvement in the physical properties of soils, viz., bulk density (from 1.40 to 1.23 Mg m^{-3}) and hydraulic conductivity (from 0.45 to 0.81 cm h^{-1}). Belur (2006) observed gradual changes in the physical properties of sodic soils of Maharashtra. The bulk density decreased while the hydraulic conductivity (HC) increased with use of gypsum, as well as its combined use with SWPMC. The HC was improved from 0.45 to 0.81 cm h^{-1} during the reclamation. The reduction in bulk density was also due to regeneration of the structure caused by improved aggregation with the addition of the organic matter present in the compost. This suggests that integration of both chemical amendment and organic conditioner, along with bioinoculants, is more beneficial in improving the air–water relationship in sodic soils.

Sagare et al. (2001a, b) also reported a smaller increase in the HC of sodic Vertisols from 0.41 to 1.05 cm h^{-1} with use of gypsum. Kharche et al. (2010) further revealed that the added advantage of increased HC observed in their study with combined use of compost and gypsum could be ascribed to dissolution of calcite, which released more calcium in addition to the calcium from the gypsum, causing a flocculating effect. Use of compost improves the efficiency of reclamation of calcareous cracking clay sodic soils and can also act as an alternative to gypsum. The significant reduction in ESP with combined application of gypsum and SWPMC is attributable to more effective reclamation, enhanced by SWPMC, which acts as an ameliorant in calcareous sodic soil, where the organic matter in the SWPMC, during its decomposition, produces organic acids that solubilize the native calcium carbonate, resulting in faster removal of exchangeable sodium and accelerating the reclamation of calcareous sodic soil.

Field investigation on farm fields, conducted to evaluate the gypsum bed technique for irrigating cotton in sodic Vertisols of the Purna valley, indicated that soil application of gypsum @ 25% GR plus surface irrigation with alkaline water passed through a 30-cm gypsum bed sustained the seed cotton yield with a higher B:C ratio (Sonune et al. 2011). This combination further reduced detrimental characteristics—such as high pH, ECe, SAR, and ESP values—and also significantly improved the HC of the soil in comparison with the control. The seed cotton yield showed a significant positive correlation with exchangeable Ca and Ks and a negative correlation with SAR and ESP. Installation of subsurface drainage at 75m spacing with 80mm diameter polyvinyl chloride (PVC) corrugated pipe in saline alkali deep Vertisol with incorporation of sugarcane trash (5 Mg ha^{-1}) or green manuring with dhaincha provided effective drainage and significantly increased the productivity of soybean and wheat by reclamation of the saline alkali soil (Bharambe et al. 2001).

Effective alternatives to conventional approaches are necessary to increase the potential of soil reclamation. Application of organic amendments in the form of green manure and crop residue is a simple practice that can prove to be a promising option in this regard. Studies on the effects of various organic amendments, in comparison with gypsum, on carbon dynamics and nutrient availability in calcareous sodic Vertisols of the Purna valley (Shirale 2014) revealed that application of organic amendments significantly enhances organic carbon, permanganate oxidizable carbon, soil microbial biomass carbon, and soil organic carbon (SOC) stock in comparison with application of gypsum and control treatment. The incorporation of dhaincha and sunhemp (*Crotalaria juncea*) in *in situ* green manuring showed the highest potential to sequester carbon in soils. Different organic amendments have the potential to alleviate carbon and nutrient stress in sodic Vertisols in a high-pH and high-ESP stress situation. Use of farmyard manure (FYM), compost, green manure, and crop residue is also recommended to reclaim the soil.

11.5 Conclusions

Soil chemical degradation, in terms of increases in the exchangeable sodium percentage and the exchangeable magnesium percentage with depth in saline–sodic Vertisols, adversely affects hydraulic and other properties that are important for crop growth. These soils contain high $CaCO_3$. Precipitation of Ca in the form of $CaCO_3$ immobilizes Ca and Mg, and dominance of Na is increased, which affects the physicochemical properties of the soil adversely. Clay dispersion leads to destabilization of the soil structure and breaking of the soil capillary network, ultimately affecting the water transmission characteristics of the soil. Sodic soils are largely dispersed and poorly aerated with low hydraulic conductivity. Addition of crop residue and green biomass to black saline–sodic Vertisols is more beneficial than use of gypsum alone in enhancing the soil organic carbon stock and soil quality, besides assisting with gradual soil reclamation.

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Carbon Dynamics in Salt-affected Soils

12

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Abstract

Salinity and sodicity are major constraints for crop production in arid and semiarid regions of the world. Soil fertility and atmospheric carbon dioxide (CO_2) concentrations are strongly affected by soil organic carbon (SOC) turnover. Salt affects soil C pools and CO_2 emission by (i) plant growth as well as C input reduction and (ii) reducing microbial activity and thus C turnover due to osmotic stress in saline soils or poor soil structure in sodic soils. Due to lesser plant growth, and C input, SOC content is low in salt-affected soils. This review has identified many technologies (including phytoremediation, changes in land use, organic amendments, irrigation and tillage) that have been practised to increase SOC stocks in salt-affected soils. Many models for SOC sequestration used by various agencies do not take into account the effect of salt and therefore, provide incorrect data on SOC dynamics in salt-affected soils of India and world. With the predicted increase in area affected by salinity, it is important to develop the management practices and technologies which will not only reclaim salt-affected soils but also increase carbon content to restore the fertility of these soils.

Keywords

Carbon dynamics · Salt-affected soils · Soil organic carbon · Soil inorganic carbon · Soil health · Carbon pool

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12.1 Introduction

Salt accumulation in soils is a major threat to sustainable agricultural production and ecosystem sustainability due to its negative effect on plant growth. It has been reported that about 6.73 million ha area in India is salt-affected which is creating a serious threat to food production of the country resulting in losses of 230 billion INR every year which is expected to rise with further increase in salt-affected area to 16.2 million ha by 2050 (CSSRI 2015). Both salinity and sodicity are major impediments for crop production, having huge impact on soil organic matter (SOM) which plays an important role in regulating physical (stabilisation of soil structure), chemical (buffering and pH changes) and biological (microbial activity) properties of soils. Both salinity and sodicity affect the process of SOM turnover, which plays a key role in greenhouse gas emission. The soil carbon (C) pool is a potential source or sink of greenhouse gases in the terrestrial ecosystem, and it has two principal components: soil organic carbon (SOC) and soil inorganic carbon (SIC). The global SOC pool is estimated at 1576 Gt C to 1 m depth (Lal et al. 2007). The global soil carbon (C) pool is greater than the atmospheric and biotic pool combined; therefore, the changes in SOM content will affect atmospheric CO_2 concentration. It is important to understand SOC dynamics which is essential for coping up with the global warming effects as there are evidences that salt-affected soils have significant potential for C sequestration (Lal 2004; Setia et al. 2013).

In this chapter, the effect of salinity and sodicity on C (organic and inorganic) dynamics, changes in C sequestration in salt-affected soils due to land use and agricultural management practices, spectral characterization of SOC in these soils and the amelioration strategies affecting SOC storage will be examined. Given the scope, it will not be possible to present the exhaustive review of all the studies carried out in different continents of the world, but the main objectives of the chapter are the processes controlling SOC cycling in salt-affected soils and the management practices that can influence SOC cycling and storage.

12.2 Physical and Chemical Properties of Salt-affected Soils

Salt-affected soils, based on their origin, nature, characteristics and plant growth relationships, are classified into three groups: (i) saline soils, (ii) sodic/alkali soils and (iii) saline-alkali soils. The physical and chemical properties of these soils affect carbon sequestration in these soils.

12.2.1 Saline Soils

As per the US Salinity Laboratory Staff (1954), these soils have an electrical conductivity of the saturated soil extract (EC_e) more than 4 dS m^{-1} at 25 °C, pH of saturated soil extract (pH_s) less than 8.5 and exchangeable sodium percentage (ESP) less than 15. Gupta and Abrol (1990) defined that saline soils of India have

pH_s less than 8.2, EC_e more than 4 dS m^{-1} and the predominance of chlorides and sulphates of sodium (Na), calcium (Ca) and magnesium (Mg).

Saline soils are mainly found in arid and semiarid climate. In arid climatic regions, saline soils may have excessive amount of boron, fluoride and nitrates. The human activities accelerating the salinization process are excessive use of basic fertilizers (such as sodium nitrate, basic slag, etc.), removing native vegetation, growing shallow-rooted annuals and excessive irrigation which increases leakage of salts to the groundwater system. The use of saline groundwater for irrigation and rise of water table bring salt to the root zone and on the soil surface. In saline soils, the fine particles are bind together into aggregates through flocculation which is beneficial in terms of soil aeration, root penetration and root growth, but excessive salt concentration causes poor plant growth.

12.2.2 Sodic Soils

The pH of sodic soils usually varies between 8.5 and 10.0, EC_e less than 4 dS m^{-1}, ESP more than 15 and sodium adsorption ratio (SAR) more than 13. However, under Indian conditions, alkali soils may have pH less than 8.2 and the ratio of $[Na^+]/([Cl^-]+[SO_4^{2-}])$ in soil solution more than 1.0 (Bajwa and Swarup 2002).

Sodic soils mainly occur in the regions with annual rainfall of 550–900 mm. As this amount of precipitation is insufficient to leach down the weathering products, Na^+ becomes dominant cation which increases SAR more than 13. The Na^+ ions replace Ca^{2+} and Mg^{2+} ions on clay surfaces, hence, the solubility of calcium carbonate, calcium sulphate and magnesium carbonates limits and precipitates. As a result ESP increases (>15). Higher pH is associated with hydrolysis of Na_2CO_3 that results in high alkalinity of soils. The OH^- ions so released result in the maintenance of high soil pH, i.e. >8.5.

Sodium has the opposite effect of salinity on soils. High sodium cause dispersion of clay particles which causes plugging of soil pores resulting in reduced soil permeability and water logging. In sodic soils, the major problems due to high sodium are reduced infiltration and surface crusting of soils. In contrary to sodium, salts that contribute to salinity such as calcium and magnesium cause flocculation of soil particles.

12.2.3 Saline-sodic Soils

Saline-sodic soils have EC_e greater than 4 dS m^{-1} and ESP greater than 15. The pH is variable and usually above 8.5 depending on the relative amounts of exchangeable Na and soluble salts. These soils form as a result of the combined processes of salinization and alkalization. If the excess soluble salts of these soils are leached downward, the properties of these soils become similar to those of sodic soils.

12.3 Importance of Organic Carbon in Soil Health

Soil organic matter (SOM) contains about 58% of carbon which plays a key role in soil health. Soil organic matter has been identified as one of the primary indicators of soil fertility due to its influence on physical, chemical and biological properties of soils (Robertson et al. 2014). SOM is measured as soil organic carbon (SOC) which is used as a common proxy for SOM (Oldfield et al. 2018). Therefore, maintenance of SOC at a reasonable level is essential for upkeeping soil health and sustaining ecological functions. The role of SOM in supporting and sustaining soil as a critical resource is gaining increased attention through initiatives promoting the concept of 'soil health' (FAO 2005; Fine et al. 2017). Soil organic matter provides nutrients critical to productivity and increases aeration and water holding capacity of soils (Brady and Weil 2007). Higher concentrations of SOM, whether native or amended, resulted in higher soil water holding capacity and nutrients and improved soil structure (Oldfield et al. 2018). Carbon input from crop/crop residues and external sources (such as FYM, composts, etc.) facilitates the formation of stable soil aggregates which in turn improves soil physical environment such as higher porosity, lower bulk density, higher infiltration and lower penetration resistance. Higher organic matter in soil increases cation exchange capacity which significantly affects nutrient retention/availability to plants. Soil organic matter serves as the storehouse of macro- (N, P, K, etc.) and micronutrients (Fe, Mn, Zn, Cu, B, Mo, etc.), and these are essential for plants to complete their life cycle. Therefore, maintaining an optimum amount of SOC in soil is essential for continuous supply of nutrients to crop plants for sustainable crop production.

12.4 Influence of Salinity and Sodicity on SOC Dynamics

The inputs of organic matter are reduced in saline and sodic soils due to decreased plant productivity. But these also affect microbial activity and therefore, can change organic matter decomposition rates. The main problem encountered by microorganisms in saline soils is the low osmotic potential of soil water outside of the cells, which causes cells to lose water. Salinity-resistant microorganisms (which can be found in Archaea, Bacteria and Eucarya) can rapidly accumulate salts (such as potassium chloride or compatible solutes) to adjust their intracellular osmotic potential (Oren 1999). Oren (1999) calculated that the synthesis of organic solutes and Na extrusion from the cells would require up to three times more energy than cell wall synthesis. Indeed, C utilization efficiency (conversion of substrate C into microbial biomass) decreases with increasing salinity (Rietz and Haynes 2003), resulting in greater CO_2 release per g substrate C. Previous study has shown that salinity changes microbial community structure (Pankhurst et al. 2001; Gros et al. 2003; Setia et al. 2012) and the fungi were more sensitive to salinity than bacteria (Pankhurst et al. 2001; Gros et al. 2003). This may have important implications for organic matter decomposition because fungi play a key role in decomposition of polymeric plant and animal residues as well as recalcitrant compounds such as lignin (Killham 1994).

Both salinity and sodicity may alter physicochemical properties of soils which affect transformation of added plant and native C in soil. Salinity decreased SOC mineralization (Laura 1974, 1977; McCormick and Wolf 1980; Sarig and Steinberger 1994; Garcia and Hernandez 1996; Pathak and Rao 1998; Sardinha et al. 2003; Wichern et al. 2006; Tripathi et al. 2006; Ghollarata and Raiesi 2007; Yuan et al. 2007; Walpola and Arunakumara 2010; Setia et al. 2010, Setia and Marschner 2012; Setia and Marschner 2013). On the other hand, there are contradictory reports on the effect of sodicity on SOC decomposition. The mineralization of added C is increased with increasing sodicity which causes dispersion of soils and thereby release of organic matter from inside of the aggregates. This organic matter becomes accessible to microorganisms (Nelson et al. 1996). A negative effect of sodicity on C mineralization has also been reported which may be due to the quality of the organic matter and anaerobic conditions in sodic soils (Abdou et al. 1975). Kaur et al. (2002) found a decrease in microbial biomass C in soils receiving continuous sodic irrigation water for 19 years in rice-wheat cropping system. Rietz and Haynes (2003) reported an exponential negative relationship between microbial biomass C and EC but a linear negative relationship of microbial biomass C with ESP and SAR. These results suggest a stronger detrimental effect of salinity than sodicity on biological properties of soils. In salt-affected soils, C and N mineralization was inhibited at higher EC with nitrification being more sensitive than ammonification (McClung and Frankenberger 1987; Rasul et al. 2006). Dendooven et al. (2010) found that decomposition of easily decomposable organic material (such as glucose) was inhibited in an extremely alkaline saline soil. Setia et al. (2011b) also found that EC was the main factor influencing soil respiration in salt-affected soils.

In saline-sodic soils, decomposition is affected by both salinity and sodicity. Wong et al. (2008) found the lowest respiration in mid salinity-low sodicity soils and the highest in low salinity-high sodicity soils. Wong et al. (2009) also found that soil respiration increased initially after addition of organic material to a highly saline sodic soil due to release of SOC sorbed onto aggregates. Skene and Oades (1995) found that treating a soil with a solution with low SAR and high EC decreased the concentration of soluble carbon. Setia et al. (2011a) found the stronger effect of salinity on C mineralization than that of sodicity.

The EC measured in fixed soil-to-solution ratio is a poor indicator of the salt stress experienced by plants and microbes because as soils dry, the salt concentration in the soil solution increases (decreasing osmotic potential). The osmotic potential of soil solution may be a more appropriate parameter for assessing the effect of salt on plant growth (Ben-Gal et al. 2009) and microbial activity (Setia et al. 2011d) than EC because osmotic potential takes into account salt concentration in the soil solution as a function of the water content.

Chowdhury et al. (2011) showed that microbial activity in saline soils was more strongly decreased by decreasing osmotic potential at given water content. Setia and Marschner (2012) found that osmotic potential is the main stressor for microbial activity in saline soils at water potential above −4.0 MPa, but matric potential is important for respiration and microbial biomass at water potential −4.0 MPa or lower (when soils are dry).

12.5 Soil Inorganic Carbon in Salt-affected Soils

Like SOC, soil inorganic carbon (SIC) also plays an important role in global C cycle. Soil inorganic carbon is mainly found as $CaCO_3$ in lower soil layers of arid and semiarid regions of the world. Soil inorganic carbon may be classified into primary (or lithogenic) soil carbonate and secondary (or pedogenic) soil carbonates. Primary SIC is inherited from calcareous parent material (limestone and other marine carbonates), but secondary SIC is formed in situ by precipitation of $CaCO_3$. Soil inorganic carbon stocks range from 695 Pg (Batjes 1996) to 1738 Pg (Eswaran et al. 1995) in soil. The higher variation in SIC stocks is due to difficulty in differentiating between lithogenic and pedogenic carbonates. In general, SIC accumulates preferentially at lower soil depths. Eswaran et al. (2000) estimated the global SIC pool to be 947 Pg to 1.0 m soil depth which accounts to approximately two-thirds of the global SOC pool. It was earlier thought that SIC is much more stable and less sensitive to agricultural practices. Lal and Kimble (2000) suggested that agricultural practices can basically alter the inorganic C cycle in soils, thereby having significant feedbacks to atmospheric CO_2 levels. In arid and semiarid regions of the world, SIC stocks can be many times greater than SOC stocks, serving as a potentially major C flux in soils where carbonates are present. Therefore, SIC stocks need to be considered in C sequestration mechanisms (Entry et al. 2004).

There are following three dominant inorganic carbon processes occurring in soils:

(a) Weathering of silicate minerals: The weathering of silicate minerals is caused by carbonic acid which is derived from dissolved CO_2 in rainwater that produces bicarbonates and acts as sink of C sequestration. In general, the rates of Ca-silicate mineral weathering in soils are typically in the order of 50–500 mol Ca^{2+} ha^{-1} yr^{-1} (Sverdrup and Warfvinge 1988; White 1995) or meaning that just 0.001–0.01 t C-CO_2 ha^{-1} yr^{-1} will be consumed (Chadwick et al. 1994).

(b) Carbonate dissolution: Dissolution of carbonates (both lithogenic and pedogenic) is another gaseous CO_2 consuming process that occurs in many soils. If the CO_2 is supplied as HCO_3 in irrigation water, then it is not clear if carbonate dissolution is acting as a carbon sink (i.e. Suarez 2000). Second, HCO_3 must be leached from the soil profile into groundwater systems (Kessler and Harvey 2001) or out into the oceanic pool (Raymond et al. 2008) where its residence time will be on the order of 1000s of years or longer. When there is incomplete leaching such as in most arid and semiarid ecosystems, carbonates dissolved in the upper soil profile often are reprecipitated deeper in the soil leading to a release of CO_2 and no net change in atmospheric CO_2 levels (Khokhlova et al. 1997).

(c) Pedogenic carbonate formation: In arid, semiarid and many Mediterranean ecosystems with high evaporative demand, carbonates are precipitated in the soil profile due to incomplete leaching of salts.

The rate of soil carbonate dissolution is greatly altered by land use change and agricultural practices. The major land use management practices influencing SIC are faulty irrigation practices, lime application and soil acidification. Irrigation water application enhances biological activity in soil which increases partial pressure of CO_2 (pCO_2). Most chemical reactions including mineral dissolution rates are accelerated by higher pCO_2 and wetter soil environment. Depending on its source, irrigation water can also contain higher levels of dissolved Ca and HCO_3 and thereby can greatly affect SIC cycling. Precipitation or net dissolution in the upper meter of the soil is determined by the source of irrigation water. In two types of cultivated soils irrigated with high ionic concentration of water (mean EC $= 1.2$ dS m^{-1}), inorganic C stocks in soils to 1 m depth were higher by 36 t ha^{-1} over native vegetation soils (Wu et al. 2008). In western USA, SIC stock was 51 ± 11 Mg C ha^{-1} higher than native sagebrush vegetation at 1.0 m soil depth after >30 years of irrigated cropping (Entry et al. 2004). Khokhlova et al. (1997) observed downward migration and concentration of carbonates below a meter after 30 years of irrigation. However, SIC was lost from the soil as bicarbonate in fields with tile drainage. Over 75 years of irrigation with fresh water in a young alluvial soil, SIC was lost at an average rate of 1.0 Mg C ha^{-1} yr^{-1} to a depth of 4.0 m mostly from pedogenic carbonates dissolution (Eshel et al. 2007). At the end of the dry season, on average SIC stocks were 15% greater in the top 30 cm soil depth than at the end of wet season reiterating significant contribution of SIC to annual net CO_2 exchange (Emmerich 2003). In Vertisols after 20+ years of irrigation, Knowles and Singh (2003) found little difference in total SIC content to 90 cm soil depth compared with remnant native vegetation. Therefore, SIC stocks can both increase and decrease under irrigated agriculture (Sanderman 2012). Much more information would be required to properly justify any SIC stock change as sequestration.

In calcareous soils, soil acidification can be partially compensated by higher calcite dissolution and thus potentially creating a net carbon sink of about 0.03–0.12 Mg C ha^{-1} yr^{-1} provided leaching of all the HCO_3 produced in soil to long-lived reservoirs (Sanderman 2012). The application of agricultural lime (aglime: limestone and dolomite) containing 12% carbon is a major carbon flux in agricultural systems. Aglime dissolution is similar to carbonate dissolution consuming one mole of CO_2 in place of releasing two moles of bicarbonate. Again it is critical to trace the fate of bicarbonate while determining the net carbon balance upon aglime application. Under acidic soil conditions, HCO_3 will react with excess of H^+ and form carbonic acid which will equilibrate with soil CO_2 subsequently releasing CO_2 back to the atmosphere (West and McBride 2005). In a low leaching environment and neutral or alkaline subsurface pH, after releasing a mole of CO_2, HCO_3 may likely reprecipitate as $CaCO_3$ making aglime dissolution as carbon neutral. However, after leaching out from soil profile, HCO_3 enters into a long-lived carbon pool, thereby proving this reaction as a net atmospheric sink. But liming also increases soil pH making the soil environment favourable to plants' growth which considerably enhances crop productivity and biomass yield absorbing a huge amount of atmospheric CO_2 (Datta and

Mandal 2018); ~1/3rd is stored as SOC in the belowground biomass balancing again the amount of CO_2 flux from dissolution of carbonates (Kuzyakov and Domanski 2000). Under long-term experiments, Fornara et al. (2011) also reported ~20% higher SOC stocks in limed than unlimed soils. Soil structure and stability of clay assemblages and clay-organic matter bonds are improved upon liming thereby protecting SOC by physical and physicochemical mechanisms (Paradelo et al. 2015). Datta et al. (2015) studied $CaCO_3$ content and SIC under different land uses in reclaimed sodic soil, saline and sodic soil. In reclaimed sodic soil, highest $CaCO_3$ content (374 Mg ha^{-1}) and SIC (45 Mg ha^{-1}) were found in soils under litchi, whereas lowest was under jamun (138 and 17 Mg ha^{-1}) up to 2.0 m soil depth. In saline soil, Kainth and *Prosopis alba*-Mustard system recorded highest $CaCO_3$ (268 and 269 Mg ha^{-1}) and SIC (32.1 and 32.2 Mg ha^{-1}) contents, respectively. Further Datta et al. (2017) found highest $CaCO_3$ (5973 Mg ha^{-1}) and SIC (717 Mg ha^{-1}) under jamun and lowest (666 and 80 Mg ha^{-1}) in *Prosopis juliflora* in sodic land (Table 12.1).

Table 12.1 $CaCO_3$ and SIC stocks (Mg C ha^{-1}) in different land uses up to 2.0 m soil depth in the parts of northwest India

Soil	Land use	$CaCO_3$	Soil inorganic C
Reclaimed sodic soil (Datta et al. 2015)	Mango (*Mangifera indica*)	162.1	19.5
	Guava (*Psidium guajava*)	305.9	36.7
	Litchi (*Litchi chinensis*)	373.6	44.8
	Jamun (*Syzygium cuminii*)	138.2	16.6
	Eucalyptus tereticornis	278.6	33.4
	Prosopis alba	171.1	20.5
	Rice-wheat	210.4	25.2
	Mean	234.3	28.1
Saline soil (Datta et al. 2017)	Frass (*Tamarix articulata*)	102.9	12.3
	Kainth (*Feronia limonia*)	267.9	32.1
	Eucalyptus (*Eucalyptus tereticornis*)	87.3	10.5
	Grassland	53.3	6.4
	Karonda (*Carissa carandas*)-Mustard	105.5	12.7
	Anola (*Emblica officinalis*)	182.8	21.9
	Bael (Aegle marmelos)	203.6	24.4
	Prosopis alba-Mustard	268.6	32.2
	Mean	159.0	19.1
Sodic soil (Datta et al. 2017)	*Prosopis cineraria*	3054.0	366.5
	Jamun (*Syzygium cuminii*)	5972.8	716.7
	Eucalyptus	3146.9	377.6
	Prosopis juliflora	666.0	79.9
	Grassland	3834.7	460.2
	Mean	3334.9	400.2

12.6 Management Practices in Salt-affected Soils as Modulators of SOC Storage

12.6.1 Phytoremediation of Salt-affected Soils

The salt-affected soils can be reclaimed through ‘phytoremediation’ by utilizing the ability of the plant roots to enhance the dissolution rate of inherent or precipitated calcite ($CaCO_3$) or dolomite ($CaCO_3.MgCO_3$) as the source of Ca^{2+} and/or Mg^{2+}. This results in increased concentration of Ca^{2+} and/or Mg^{2+} in soil solution to effectively replace Na^+ from the cation exchange complex. Phytoremediation helps in the promotion of soil-aggregate stability and creation of macropores that improve soil hydraulic properties and root proliferation (Qadir et al. 2007) which helps in greater plant-nutrient availability in soil, thereby significantly effecting C sequestration in soil.

The plant material added to sodic or saline-sodic soils as a part of the phytoremediation process leads to organic C sequestration, and the rate depends on several soil and environmental factors like texture and mineralogy, moisture regime and temperature control. In addition, the quality and quantity of organic matter added via plant shoots and roots have significant effect on SOC turnover and storage in the soil profile. Also, the plant species used for phytoremediation have a wide range in their decomposition and turnover rates and C storage in the soil (Six et al. 2002; Torn et al. 1997).

12.6.2 Changes in Land Use in Salt-affected Soils

Depending on the magnitude of degradation in sodic and saline-sodic soils, a large fraction of original carbon pool ranged between 10 and 30 Mg C ha^{-1} have lost (Lal 2001). The sequestration of C is important for the soil to perform various functions like productivity and environmental (Lal 2004). The changes in land use have significant effect on C sequestration. Previous studies have shown that cultivation of appropriate crops, shrubs and trees on sodic and saline-sodic soils may increase soil C through biomass production (Garg 1998; Kaur et al. 2002).

Garg (1998) evaluated the SOC build-up in an alkali soil under the four tree land uses (Kikar [*Acacia nilotica* (L.) Willd. ex Delile], Shisham [*Dalbergia sissoo* Roxb. ex DC.], mesquite [*Prosopis juliflora* (Sw.) DC.] and Arjuna [*Terminalia arjuna* Bedd.]). Organic C was higher in the soils under Shisham and mesquite because these species increased activity of microorganisms in upper 0.6 m soil depth due to decreased Na^+ levels in soil facilitating decomposition of leaf litter and root decay leading to accumulation of humus. Singh and Gill (1990) found the C sequestration after 20 years of planting of different species of trees in an alkali soil, and the C sequestration rate was 0.2–0.8 Mg C ha^{-1} $year^{-1}$. They found maximum C sequestration in soil with *Prosopis juliflora* (9.3 g kg^{-1}) (Fig. 12.1).

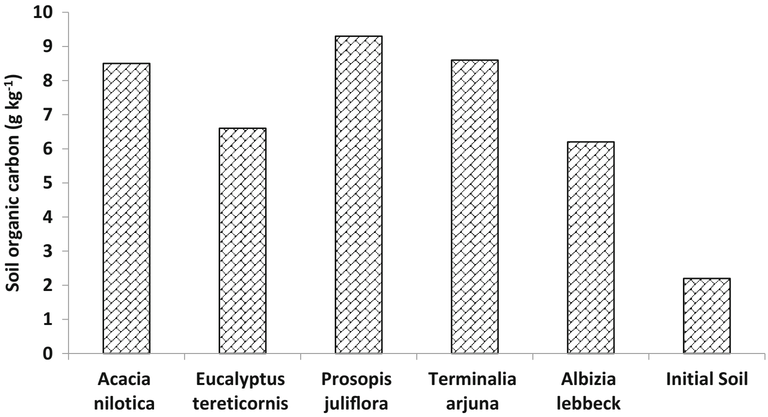

Fig. 12.1 Ameliorative effect of 20-year-old tree plantations on soil organic carbon enrichment at 0–15 cm depth of an alkali soil (Singh and Gill 1990)

Datta et al. (2015) studied the influence of land uses (guava, litchi, mango, jamun, eucalyptus, prosopis and rice-wheat cropping system) on distribution of organic carbon pools up to 2.0 m soil depth in a reclaimed sodic soil of semiarid Northwest India. They found maximum SOC storage (133 Mg C ha^{-1}) including passive pool C (76 Mg C ha^{-1}) in the soils of guava orchard. Adoption of these management practices not only rehabilitate the salt-affected soils but also sequester atmospheric CO_2. In the degraded Shiwaliks of the lower Himalayas, Saha et al. (2014) studied the land-use changes effect on SOC distribution in soil profile (up to depth of 1.05 m) under forest, grass, cultivated and eroded lands. They found highest (83.5 Mg ha^{-1}) and lowest (55.6 Mg ha^{-1}) SOC stocks in soil profile under forest and eroded lands, respectively.

12.6.3 Organic Amendments

Organic matter facilitates the formation and stability of soil aggregates through the bonding or adhesion properties (Diacono and Montemurro 2010). The aggregate stability is improved by reclamation of sodic soils. The Ca^{2+} ions in compost decrease the proportion of Na^{+} in the exchange complex and step up the leaching of exchanged Na^{+} (Qadir and Oster 2004) thereby enhancing flocculation of clay minerals which controls erosion in saline soils. Substantial flocculation as well as formation of a large number of soil aggregates was observed when different combinations of organic amendments were applied in a saline soil (Oo et al. 2013). Due to aggregate stability, other soil physical properties such as soil porosity, water infiltration and water holding capacity are improved. Wang et al. (2014) found a decrease in EC by 87% and ESP by 71% but increase in organic carbon by 96%, when a mixture of organic wastes was applied in a coastal saline soil suggesting the effectiveness of combined application of different amendments for reclamation of salt-affected soil.

Soil biological functions are improved through exogenous applications of organic matter to cropland (Diacono and Montemurro 2015). Organic material types incorporated into the soil can modify the C and N mineralization pattern in saline conditions (Walpola and Arunakumara 2010). The microbial activity in salt-affected soils was significantly improved by combined application of rice straw and pig manure than rice straw and manure alone (Liang et al. 2005).

The municipal solid waste (MSW) can be used as an organic amendment to restore the fertility of saline soils. MSW composting is an important recycling tool to tackle environmental and health issues emerged with its disposal as land filling. Its application may also help in enhancing the productivity of salt-affected soils. In a mustard-pearl millet cropping system, use of different organic amendments such as municipal solid waste compost (MSWC), gypsum-enriched compost (GEC) and rice straw compost (RSC) in sole or combined application with chemical fertilizers as reclamation agents as well as their effect on chemical and biological properties of saline soil has been studied (Meena et al. 2016). Significantly higher soil organic carbon was observed under integrated use of 25% recommended dose of fertilizer along with organic amendments (RSC@3.5 Mg ha^{-1} + GEC @ 3.5 Mg ha^{-1} + MSWC@ 4 Mg ha^{-1}) over control plot after harvesting of mustard and pearl millet. Therefore, incorporation of organic manure in soil can be an effective low-input alternative to reduce the harmful effects induced by salinization and improving C storage in soils.

12.6.4 Irrigation

In saline soils the basic method for *amelioration* is the leaching of salts, while in alkali soils the application of chemical amendment is also necessary. These amelioration strategies have significant impact on SOC concentration in soils. Recently in many semiarid and arid countries of the world, there is an increase in irrigation with marginal quality waters such as treated urban wastewater. Ganjegunte et al. (2018) evaluated SOC dynamics in salt-affected soils upon treated municipal wastewater irrigation. At 0–60 cm soil depth, the average SOC concentrations were enhanced between 3 and 5 Mg ha^{-1} under different treatments after 6 years. Mancer and Bouhoun (2018) found decrease in C mineralization when soils were irrigated with artificially salinized water. Common soluble cations found in irrigation waters are Na^+, Ca^{2+}, Mg^{2+} and K^+ which may play a key role in C mineralization. Decomposition in saline soils is enhanced by Na^+ and K^+ ions where former having more influence than K^+ (Setia et al. 2014). Binding of organic matter as well as C stabilization is enhanced by divalent cations, particularly Ca^{2+}, whereas Mg^{2+} ions have a little effect. Mancer and Bouhoun (2018) also found that decline in C mineralization in soils irrigated with NaCl solutions was higher than the solutions of $CaCl_2$ and $MgCl_2$. These results suggest that the type of salts significantly influences C mineralization in soil.

12.6.5 Tillage

Tillage affects physical, chemical and biological properties of soil. Soil bulk density, porosity and water holding capacity are the main indicators of physical and hydraulic properties of soils as influenced by tillage (Strudley et al. 2008). Intensive tillage facilitates disruption of aggregates which enhances loss of SOM, thereby contributing to climate change through higher CO_2 emissions (Parras-Alcántara et al. 2013). Management of crop residues on the soil surface are closely related to tillage effects in sodic soils. In sodic soils leaching of salts from surface to deeper layers is facilitated by tillage (Sadiq et al. 2007). Qadir et al. (2001) and Wong et al. (2010) reported improvement in structure and fertility of sodic soils under tillage. In sodic soils SOC mineralization was increased by tillage through changing organic matter distribution in soil profile (Wong et al. 2010). Singh et al. (2016) found an increase in SOC in sodic soils after medium- to long-term tillage (5 and 9 years of tillage) by modifying the distribution of crop residues. In a fine-textured Vertisols, tillage and crop residue management significantly affect soil organic matter and microbial activity at surface layers and movement of salt to deeper soil layers (Dalal 1989). Continuous tillage for 9 years increased SOC by 35% in surface soil and 39% in deeper soil as compared with untilled lands (Singh et al. 2016).

12.7 Spectral Characterization of Organic Carbon in Salt-affected Soils

The laboratory techniques (chemical and dry combustion methods) used for soil organic carbon quantification require lots of capital and time, and chemicals used for SOC analysis are hazardous to environment (Srivastava et al. 2015). Nowadays, diffuse reflectance spectroscopy techniques in different categories of infrared (IR) waves (near IR and mid IR) have been used for estimation of SOC owing to their easy way of sample preparation (soil sieving) and non-destructive nature (Morra et al. 1991; Ben-dor and Banin 1995; Shepherd and Walsh 2002; Srivastava et al. 2004; Brown et al. 2005; ViscarraRossel et al. 2006; Summers et al. 2011; Srivastava et al. 2015). In visible and near-IR spectroscopy, soil reflectance signatures are characterized over whole region starting from visible (400–700 nm) to near-IR (700–2500 nm), because SOC have specific absorption peak at the visible region because of electronic transitions of atoms, weak overtones and the combinations related to the vibrations (bending and stretching) in molecular bonds of light atoms in the infrared region (Dalal and Henry 1986; Clark 1999). Specific property of a soil sample can be predicted with the help of characteristic features, such as chemical bonds of H^+ attached to C atoms, which enables to measure organic C using the NIR technique based on the use of both calibrations and chemometrics techniques with the help of absorbances at specific wavelengths coupled with mathematical and statistical techniques (Shepherd and Walsh 2002).

Spectral reflectance values are used for the development of statistical models (empirical in nature) to produce the best correlation by fine-tuning process with the predicted property (Minasny et al. 2011; Summers et al. 2011; Izaurralde et al. 2013; Srivastava et al. 2015; Ji et al. 2015; England and Rossel 2018). But these empirical models have strong site dependence. Therefore, emphasis has been given on the development of region-specific spectral models.

12.7.1 Spectral Behaviour of Soil Carbon

Soil reflectance spectra are influenced by basic soil properties like soil moisture, organic matter content of soil, clay type including Fe and Al oxides and its content (Bowers and Hanks 1965). Soil organic carbon is significantly correlated with soil moisture content, soil type, texture, etc. The prominent absorption features of reflected spectra were followed around 1400, 1900 and 2200 nm (Ben-dor et al. 1999; Shepherd and Walsh 2002) and associated with clay minerals and moisture content, for example, absorption peak due to OH features of free water (1400 and 1900 nm) and clay lattice (1400 and 2200 nm) (Hunt 1982). When the absorption feature was transformed to first derivative becomes more prominent. But valuable information on soil properties can be extracted from subtle differences in spectral shape which help to remove overlapping absorption features of many soil organic and inorganic components. Srivastava et al. (2015) found significantly strong SOC correlation at 1400, 1900, 2200, 2250 and 2300 nm under non-salt-affected soils of Indo-Gangetic alluvial Plains (IGP) of India. Knox et al. (2015) compared the mid-infrared (MIR) and VNIR-MIR for predicting SOC, but the significant peak (at 2700 nm) was associated with a double and broad double feature in C-O and Si-O stretch regions, respectively, and O-H fundamentals. Researchers (Hummel et al. 2001; Mouazen et al. 2007; Lee et al. 2009; Morgan et al. 2009) have shown the optimum range to predict SOC in near-IR, i.e.1650–2500 nm. The importance of visible and near-IR range for organic carbon calibration has been reported by many researchers (Ben-dor and Banin 1995; Ingleby and Crowe 2000; Cozzolino and Moron 2006; Mouazen et al. 2007; Vasques et al. 2008). Most of the predictions based on spectral reflectance have been made for non-salt-affected soils, but the information on SOC estimation in salt-affected soils using spectroscopy is very little. Srivastava et al. (2017) compared the spectra of non-salt-affected ($EC<4.0$ dS m^{-1}) and salt-affected soil (between 4.0 and >50 dS m^{-1}) (Fig. 12.2a), and they found out that the magnitude of diagnostic absorption features of 1st derivative transformation data was strongly prominent at 1900 nm followed by 1400 and 2200 nm and also proved that an increase in soil salinity level leads to shift in absorption peaks at 1900 nm towards the higher wavelength (Fig. 12.2b).

12.8 Modelling SOC in Salt-affected Soils

A model is a mathematical representation of the real system with well-defined boundaries and explores the relations amongst various components, increases insight into processes and examines the consequences of management and further

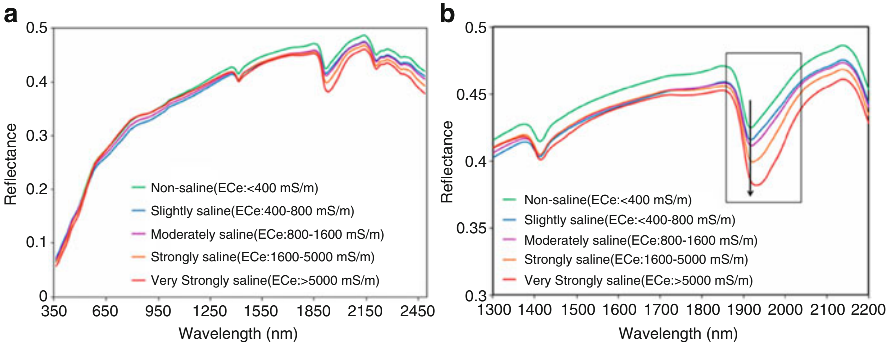

Fig. 12.2 Spectra of (**a**) different soil salinities between 350 and 2500 nm region. (**b**) Increase in salinity leads to shift in absorption peak towards higher wavelengths

possibilities for modification. SOM models can be broadly classified into static and dynamic models. In static models, environmental variables remain constant. The single homogenous compartment and two compartment models (Jenkinson 1990) are classified under static models. In dynamic models, environmental variables vary with time. The non-compartmental and multi-compartmental decay (Jenkinson 1990) are classified under dynamic models which can be further categorised into organism-oriented and process-oriented models (Paustian 1994). According to Manzoni and Porporato (2009), there are 250 models used for predicting SOC dynamics and nutrient turnover in different parts of the world. These models differ in underlying assumptions and the processes responsible for SOM decomposition. Nevertheless, most of these SOM models divide SOC into different pools with distinct properties and rate constants.

The process models are based on linear, exponential decay and ordinary differential equations first-order kinetics. These process-based models are devised on assumptions that SOM pools are parts of a chain of differential residence times linked by C flows. Commonly included models in this category are CENTURY (Parton et al. 1988), RothC (Jenkinson 1990), DAISY (Jensen et al. 1997), CANDY (Franko et al. 1997), DNDC (Li et al. 1997), etc. Smith et al. (1997) evaluated nine SOC models against data from seven long-term experiments under arable land, grassland and woodland. Out of nine models, six models (RothC, DNDC, CANDY, CENTURY, DAISY and NCSOIL) performed well over the three models (ITE, Verberne and SOMM). Izaurralde et al. (1996) evaluated five SOC models (RothC, DNDC, CENTURY, EPIC and SOCRATES) at site-specific and a regional level in Canada. Among these models, CENTURY was best for simulating long-term prediction of SOC trends at regional level but SOCRATES at site-specific levels. Among all the models tested by Smith et al. (1997), RothC (Jenkinson et al. 1987; Coleman and Jenkinson 1996) and CENTURY (Parton et al. 1988) are most widely used for studying the impact of climate and land use change on SOC. However, RothC requires fewer inputs than CENTURY to simulate SOC. Final stocks of SOC in these models are determined by adding output from multiple pools of differential decay rates. RothC has also been successfully applied in China (Guo et al. 2007), Kenya (Kamoni et al. 2007), Zambia (Kaonga and Coleman 2008) and West Africa (Nakamura et al. 2010), but it was not calibrated for salt-affected soils. Setia et al. (2011c, d), first time in the world, modified the RothC for saline soils, and they introduced two modifiers in this model: the modifier accounting for the influence of salinity on decomposition rate and the modifier for plant input. Setia et al. (2012) also developed an iterative approach to estimate the steady-state C content of the nonsaline soils prior to the onset of salinization from the present-day SOC content measured under saline conditions. Setia et al. (2013) used this iterative approach to predict global SOC stocks before the onset of salinization, and they estimated that world soils have lost an average of 3.47 Mg ha^{-1} SOC due to salinity relative to soils not affected by salt. If the extent of salt-affected soils increases in future climate, world soils may lose 6.8 Pg SOC due to salinity by the year 2100. The modelling results indicated a greater decrease in SOC in saline than in nonsaline soils of India and Australia in the future climate. Thus, the previous projections of the decrease of SOC in saline soils have been underestimated; this also means that saline soils will emit more CO_2 than previously thought.

12.9 Conclusions

Salinity decreases SOC decomposition, but the effect of sodicity on C mineralization is contradictory. Sodicity can increase C mineralization due to dispersion of soil particles, but a negative effect of sodicity on C mineralization may be due to anaerobic conditions in sodic soils. Salinity is measured as electrical conductivity in the saturated paste (EC_e) or in soil/water ratios, but this may not be a good measure of the osmotic stress experienced by microbes in saline soils. The osmotic potential of the soil solution is a better parameter for evaluating the effect of salinity on microbial activity in soils. Currently, models for SOC stocks, SOC sequestration and CO_2 release used by various agencies do not take into account the effect of salt and therefore, provide incorrect data on regional and global level. However, it has also been shown the importance of including a salt rate modifier for decomposition and plant input into SOC modelling as the predicted global SOC stocks were substantially lower than previously estimated. Physical, chemical and plant-based approaches singly or in combination can reclaim salt-affected soils. Many management practices (like phytoremediation, land use changes, organic amendments, irrigation, tillage, etc.) have not only reclaimed the salt-affected soils in different parts of the world but also increased the carbon storage in these soils. For wider adoption and implementation of improved agricultural management practices, enhanced collaboration and communications are required amongst scientists, farmers and policymakers, to restore the fertility of salt-affected soils.

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Engineered Polymeric and Nano-materials for Taming Salty Soils and Waters Used for Crop Production

13

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Abstract

World food production systems, mainly cropping systems, are set to deal with exceptional stress for matching agricultural food production demand with the growing population, particularly in the backdrop of climatic changes. The increase in production cannot be attained with the same approaches as were followed in the past. A large extent of less productive lands (including salt-affected soils) in India and the world represent opportunity for boosting sustainable food production via land recovery, enhanced productivity, resource conservation practices, and by enhancing biological functions of soil. The soluble salts present in the water and soil, including groundwater and surface water, pose excessive threat to the productivity of land. Odd practices, such as land clearing and poor irrigation management, have considerably increased the magnitude of the problem. High concentration of salts in the soil is harmful to plants as it restricts uptake of water and nutrients by the plants.

There are several approaches for managing salty lands, including minerals-based reclamation, but these are very expensive. Material science as an emerging field of science may play a significant role for developing efficient reclaimants for managing these salt-affected marginal lands. Nanotechnology, polymer science and microbiology are some of the promising fields to play role in developing

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smart, efficient material and technology. Although nanotechnology in the areas of environmental and agricultural research and development is at emerging stage, it can be effectively used in understanding and creating improved materials, devices and tools, and in exploiting the nano-properties for managing salty lands and waters. Nanotechnology application in agriculture is an approach that can be used as a tool for detection and treatment of plant diseases, which increases availability of nutrients to plants, thus enhancing soil fertility, health and crop production. The potential of this technology is yet to be exploited in salt-laden lands and water management, and in the agricultural system as a whole. Once recognized, it is expected to bring a major change in agricultural production.

Keywords

Nanotechnology · Polymer science · Microbiology · Marginal lands · Soil salinity · Sodicity · Reclamation

13.1 Introduction

Soil productivity is partially or even completely lost due to buildup of excess salts in the soil. Soil salinization is as an ecological problem often attributed to natural influences rather than anthropogenic activities. Salt accumulation occurs in soil either naturally or due to anthropogenic influences, and this presence of salts is the main cause of crop failure. It is called primary salinization when the soil salinity occurs naturally like the sea salt marshes. While secondary salinization appears when the soils originally has low salt concentration and become saltier due to irrigation (especially with high salt content groundwater), poor drainage or/and unmanaged agricultural practices (Zhu 2007). The secondary soil salinity has increased at a very rapid rate due to the continuous use of saline groundwater which has increased with time because of increased pumping, as well as due to other problems such as poor drainage, exposure to saline or sodic subsoil, and erosion and movement of subsoil salts to surface due to canal seepage, etc. Salt-laden soils are a result of climate and inappropriate soil management, mainly spread in arid and semiarid areas. From management point of view, salt-affected soils can be divided into three categories: (1) saline soils with soluble salts, (2) sodic soils with Na^+ on clay complex, and (3) soils with both salinity and sodicity, called saline-sodic soils. These categories are further identified depending on salt content and type, amount of sodium present, and soil alkalinity. Crop plants growing in such soils are often stressed, even under enough water accessibility. This is because the osmotic potential of soil hampers the plant roots uptake of water. Salt-affected soils feel wetter compared to the rest of the field, with a white surface crust when dry. Salt-affected lands cover large parts across the world, including Indo-Gangetic plain to great Hungarian plain, drylands of China, Russia, Israel, and the United States of America. According to the Food and Agricultural Organization (FAO 1989), saline soils occupied an area of 397 million hectare, and the sodic soils occupied an area of

434 million hectare, on the world basis. Of the 230 million hectares of cultivated land, 20 % is salt-affected. The extent is as high as 30% in countries like Argentina, Egypt, and Iran (Ghassemi et al. 1995). In India 6.75 million ha area is salt-affected (saline, sodic, and saline-sodic). Out of this, 1.2 million ha area falls in Indo-Gangetic plain. The salt-laden soils are not only unsuitable for crop production but also vulnerable to degradation. The problems, such as lack of porosity, high sodium concentration, water logging, and hydraulic constraints, make these soils less productive. Saline soils are mainly rich in neutral salts, like SO_4^{2-}, Cl^-. On the other hand, sodic soils have high amounts of CO_3^{-2} and HCO_3^- of sodium and are capable of alkaline hydrolysis. High concentration of Na^+ cations (sodic condition) results in hard structured and impermeable soil. Soil sodicity arises when Na^+ ions move down with water flowing through soil pores. The Na^+ ions get bound to the clay particles which affect shrinking and swelling properties of the soil. Dispersion and swelling of clay are the main reasons that make these soils unfit for crop production (Bhardwaj et al. 2008). Sodic soil remediation is very challenging in itself, with gypsum ($CaSO_4.2H_2O$) being quite viable option. Soil salinity inhibits seed germination and water uptake by plants. Besides this, salinity also affects soil physicochemical properties of the soil. Also, salt-affected soils have adverse impacts on soil microbial communities, soil structure, water recharge, and are characterised by poor nutrient availability.

13.2 Conventional Options for Managing Salt-affected Soils and Waters

13.2.1 Remediation of Sodic Soils and Waters

As it is, sodic soils contain soluble salts, mostly CO_3^{2-} and HCO_3^- of Na^+ having pH greater than 8.5 and exchangeable sodium percentage (ESP) >15. These soils are often referred to as black alkali soils due to the black color imparted by dispersed soil organic matter in the presence of Na_2CO_3. Sodic soils are highly dispersed and therefore have very low hydraulic conductivity. Very often they have a hard impervious $CaCO_3$ layer at depths lower than 30 cm that acts as a barrier to movement of water and subsequent crop growth, as well as for removal of salts from salt solution. The presence of high amount of sodium is characteristic of these soils, mostly in form of CO_3^{2-} and HCO_3^-, but chlorides and sulfates are also present. Common characteristics of sodic soils include low primary productivity of land, black color when wet due to dispersion of organic matter, powdery when dry (under extreme sodicity), cracked and dry under medium sodicity, and soft under wet conditions. The best reclamation of sodic soil is possible only after the sodium from the clay exchange sites in removed into soil solution and then leached out. Sodic waters are those which have sodium adsorption ratio (SAR)>13 or residual sodium carbonate (RSC) > 1.25 me L^{-1}. Sodic waters have direct and indirect effects on crop productivity and must be neutralized for sodicity before use for productive agriculture. Therefore, sodic soils and water are usually reclaimed with use of amendments which contain Ca^{2+} to replace Na^{+} in the soil or water. The Ca^{2+} containing amendments from various sources have been tested for their efficacy and found useful for sodic soil management. Several mineral and organic amendments have been tested and found effective depending on soil conditions and availability of resources.

13.2.1.1 Mineral Amendments

Gypsum ($CaSO_4$. $2H_2O$) is one of the most common mineral amendments used for reclaiming sodic/alkaline soils. Upon dissolution of gypsum Ca^{2+}, ions are released into soil solution, and these help in replacing Na^{+} from the clay complex, which is then leached out of the profile. Gypsum also plays a significant role to improve soil structure so that leaching can effectively remove salts from the root region. Sodium replaced from clay sites is leached out from the soil by application of irrigation water or rainfall. Gypsum helps in reclaiming soil by decreasing the electrical conductivity (EC) and exchangeable sodium percentage (ESP) of the soil. One ton of gypsum per acre results in around 10 % reduction in ESP in 0.5 foot area of a sandy soil and 3% in a clay soil. Reclamation using gypsum may be required in more amounts for more years to reclaim the soil to lower depths. Being an effective amendment, fine quality gypsum is less available nowadays. The agro-industrial waste products, such as phospho-gypsum, can be utilized as an alternative to gypsum, though impurities such as fluoride and presence of radioactive elements can be a problem with these materials. Since phospho-gypsum is a by-product of phosphate industry, it is cheaply available and thus being more cost-effective for sodic soil reclamation. It has been reported that phospho-gypsum dissolves faster than mined gypsum and hence produces more electrolyte concentration during an infiltration event (Keren and Shainberg 1981). The acidic property of phospho-gypsum is beneficial in decreasing aggregate dispersion through increased flocculation of soil particles and aggregate attachment by iron, calcium, and aluminum released by dissolution of calcite (Oster 1982). Phosphoric acid can also be used, although its effectivity is less understood. Compared to phospho-gypsum, the cost of phosphoric acid is around one-third (Gharaibeh et al. 2010). Gharaibeh et al. (2010) reported that phosphoric acid decreased more sodium content in the soil than phospho-gypsum at any given pore volume, thus requiring less amount of water. A general recommendation for use of phosphoric acid is a rate of 450 kg ha^{-1} and at least two pore volumes of water for leaching. The amount of gypsum incorporated in the soil can be calculated from the amount of exchangeable Na^{+} replacement by Ca^{2+}. Sulfur in the form of iron sulfate ($FeSO_4$. $7H_2O$), aluminum sulfate (Al_2 $(SO_4)_3$.18 H_2O), lime-sulfur solution (25% sulfur), H_2SO_4, etc. can also be used for reclamation of sodic soils. Sulfuric acid helps to maximize the dissolution of calcite in saline-sodic soils (Gupta and Abrol 1990; Mace et al. 1999; Qadir et al. 2001). H_2SO_4 increases the solubility of Ca^{2+} and Mg^{2+}, lowers sodium adsorption ratios and pH, and increases EC. H_2SO_4 contributes to better reclamation in the calcareous sodic soils and clays by HCO_3^{-} production and gypsum supersaturation, besides lowering pH and increasing EC. These sulfur materials (iron sulfate, sulfuric acid, and aluminum sulfate) do not supply any calcium. They only reclaim when soil contains lime. If native lime is not present in the soil, then gypsum or other materials which contain calcium are used. In the sodium removal process, the speed of activity is ranked fast to slow in the order: sulfuric acid, gypsum, and sulfur. The removal of salts from soil using sulfuric acid is performed by increasing the water flow rate through the soil, but special equipment for the safe handling of acid is needed. Microbiological oxidization of sulfur into H_2SO_4 is needed for its effectiveness in dissolving soil lime.

13.2.1.2 Organic Amendments

The organic matter application has various positive effects on soil, such as improvement in soil structure, water holding, nutrient retention and protection against erosion, etc. (Roy et al. 2006). Various organic materials, such as farmyard manure (FYM), agroresidue, and compost, can be applied as amendments to improve the soil fertility and its health as well as remediation of the salinization (Diacono and Montemurro 2010; Montemurro et al. 2010). These materials also help in improving exchangeable K^+, thus reducing the attachment of exchange complex when applied to salt-affected soils. FYM with saline water also helps in improvement of infiltration rate and therefore reduction in effect of salts. The soil porosity and aeration can be improved by decreasing soil bulk density with the use of organic materials.

Biochar (pyrolyzed organic matter) can also be used to partially reclaim salt-laden soils, but the output highly depends on its properties. Biochar is a carbonaceous residue formed under anoxic conditions at high temperatures (300 to 1000 °C). It is beneficial in improving physical, chemical, and biological properties of salt-laden soils (Crombie et al. 2013; Uchimiya and Bannon 2013; Huff et al. 2014). It also improves water-holding potential and porosity of these soils. However, these effects highly depend on raw materials and pyrolysis (Spokas et al. 2012; McBeath et al. 2014; Vaccari et al. 2011; Novak and Busscher 2013). Kolb et al. (2009) observed improvement in total N of a sandy loam spodosol after adding mixed feedstock (pinewood/bull manure/dairy manure, as 1:2:1), but any such effects were absent in clay loam Alfisol. Biochar in the salts containing soils also help in boosting soil organic carbon (SOC), nutrients (e.g., Zn, Mg, Mn, Ca, K), surface area, cation exchange capacity, stabilization of soil structure, and replacement of sodium ions by calcium (Ca^{2+}). It also improves physical properties of soil (Rajkovich et al. 2012; Usman et al. 2016; Yue et al. 2016; Zheng et al. 2017). But the production of biochar is associated with high energy costs; therefore its high application rates in salinity and sodicity affected areas are still a major challenge for its widespread use. Moreover, the information of its applications toward the long-term application of salt-laden soils is relatively less available (Saifullah et al. 2018). Other organic amendments, for example, compost and poultry manure, also improve the physical properties of these soils (Walker and Bernal 2008; Jalali and Ranjbar 2009; Lakhdar et al. 2009).

Fly ash is yet another material which has been tried for remediation of salt-laden soils. Fly ash is a coal residue formed during combustion in thermal power plants. It can be utilized for improving soil properties and is an effective nutrient source for plants. It is also effective in improving soil fertility and health and crop performance. Fly ash contain high amount of nutrients, such as Na, Mg, Ca, K, Zn, and Fe which are very beneficial for crop production. Amendment of sandy soil with fly ash up to 40% has been reported to increase soil porosity up to 53% and water-holding capacity up to 55% and also increased water for plant uptake (Taylor and Schumann 1988; Singh et al. 1997). Fly ash has capacity to enhance flocculation of dispersed soil particles, water penetration, and replacement of Na with Ca and allows root penetration into deep soil layers (Jala and Goyal 2006). It also reduces soil bulk density, improves soil texture, optimizes pH, improves water-holding capacity, improves soil aeration, and decreases the mobility and availability of metals in soil. However, it has some limitations as well, such as reduced bioavailability of nutrients because of high pH and high concentration of boron.

Another agro-industrial by-product which has proven effective in countering sodicity/salinity is pressmud. Pressmud is a waste by-product of sugar industry that was used as an organic amendment for crop growth and production (Raman et al. 1999). It has shown positive effects on physical, chemical, and biological properties of the soils and therefore can contribute to optimum crop yield (Yaduvanshi and Swarup 2005; Srivastava et al. 2014). Its effectiveness is primarily due to the increase in microbial population caused by addition of organics and sugars that may regulate the soil temperature and moisture and the humus content. Pressmud helps to increase the nitrogen availability in soil. This might be due to development of favorable conditions for the soil organisms involved in nitrogen transformation (Muthuraju et al. 2005; Parasuraman and Mani 2001).

13.2.2 Remediation of Saline Soils

Saline soils have soluble salts, mostly, which hinder plant development and growth to the extent that crop productivity declines appreciably. Most important characteristic of the saline soils is that they have electrical conductivity (EC) > 4 dS m^{-1}. These soils have poor structure and low organic matter and contain Cl^- and SO_4^{2-} of sodium and calcium and magnesium. Saline soils are formed in the regions where accumulation of salts due to topography, mismanagement, or climate occurs. The management of saline soils is possible by removal of salts by leaching with excess water or exclusion of salts from active root zone.

13.2.2.1 Leaching

It is the most effective method of removing salts from the root region of soils. The mechanism involves the infiltration of fresh water through the soil surface and dissolving salts as it moves down the profile. The salt is most effectively leached out in this process. Leaching should preferably be done when there is deep groundwater table and low soil moisture content. Leaching during the summer is least effective as water is evaporated.

13.2.2.2 Scraping

It is a mechanical method to **r**emove the accumulated salts from the soil surface, which temporarily improves crop growth; however disposal of salts is still a big problem.

13.2.2.3 Flushing

Flushing involves the washing off salts accumulated on the soil surface, but amount of the flushed salts is low. Therefore, this method does not have much practical significance.

13.2.2.4 Irrigation Management

Water management using proper irrigation practices helps increasing crop yields even under saline conditions. Most plants need an uninterrupted supply of water to grow, resulting in high yields. Irrigation helps in increasing moisture content of the soil, whereas salt concentration in the soil solution decreases which helps in crop growth.

During evapotranspiration process, salt concentration in the soil increases which results in building high osmotic pressure in the soil. This hampers the capacity of plant to absorb water from the soil. Thus, infrequent irrigation in saline soil shows adverse effects on plants growth. Apart from this, frequent irrigations result in minimizing the salt concentration in soil. Therefore, irrigation should be given more frequently to the crops grown in saline soils than those grown in nonsaline conditions. Sprinkler and trickle or drip irrigation methods are the most important means for frequently irrigated salt-affected soils, particularly for the leaching of salts from the soil profile.

13.2.2.5 Mulching

Leached salts have a tendency to appear on the soil surface during high evapotranspiration periods falling between two irrigations or during fallow periods. In shallow water table, the soil salinity is exceptionally high, and therefore the salinity of groundwater is also high. The root zone salinity is controlled when evaporation is reduced and that encourages downward flow of soil water. Sandoval and Benz (1966) and Benz et al. (1968) reported that soil salinity improved in 3 years period when bare fallow and straw mulch is used. Their results showed that for the reduction in salinity, bare fallow mulch and straw mulch should have been maintained. Fanning and Carter (1963) also reported the significant decline in salt concentration from root region of plots using mulch. Periodic sprinkling of mulched soils was reported to result in removal of salts at high concentrations leading to greater leaching efficiency as compared to flooding or sprinkling of bare soil (Carter and Fanning 1964).

13.2.2.6 Crops and Cropping Cycle Selection

Other practices which have been found effective include selection of cropping sequences including rice, berseem crops having frequent irrigation requirements, and adequate drainage, thus reducing soil salinity more effectively. In the absence of proper soil management practices and lack of needed water supply, salinity is influenced inadvertently under diverse crop rotations. Therefore the best cropping sequences can be planned only when we have the right knowledge about the salt balances in the root region in various crop rotations during and after reclamation (Massoud 1976). By selecting a proper crop rotation, a producer can maintain good soil productivity. The salt content of soil may upsurge in one crop and decline in the following crop. Approximately, there is about tenfold increase in salt resistance among the crops. In areas where water tables are saline and soil permeability is relatively low, attaining nonsaline surroundings would not be cost-effective. So the best alternative option is to select crop with high yield potential in saline conditions rather than seed placement or standing a plant in furrow-irrigated farmland.

13.3 Engineered Materials for Managing Salty Soils and Waters

Engineered materials are materials that perform better than conventional materials and have high efficiency too. Conventional materials for reclamation of salty soils and waters have certain limitations which make them inefficient, unsafe, or unavailable for effective use on a large scale. However, engineered materials might play an important role due to their increased efficiency, decreasing the input use and economizing reclamation process. The possibilities are immense, yet the area and problem-specific solutions are needed to be explored and developed. There are several options available which play a significant role in taming salty lands and waters for productive agriculture.

13.3.1 Polymeric Materials

In simpler words, a polymer is a large molecule made up of millions of light and simple molecular repeated units. Polymers have a broad range of properties, so they play major role in daily life. In agriculture, synthetic polymers have played a key role in enhancing plant development and facilitating crop production. Some of the most common uses have been as mulches, in green houses, for irrigation, fumigation, transpiration and water distribution, etc. Linear polyacrylamide is one polymer which has been used as soil conditioner in several countries for enhancing crop productivity. Anionic polyacrylamide (PAM) represents an environment-friendly polymeric amendment for soil, controlling water runoff and soil erosion (Lentz et al. 2002; Entry et al. 2002; Al-Abed et al. 2003). The benefits of PAM are as follows: (1) increasing soil aggregation (Ben-Hur and Keren 1997; Green et al. 2003; Ajwa and Trout 2006), (2) stabilizing soil structure against shear forces (Lentz and Sojka 1994), (3) boosting water infiltration rate and reducing sealing of soil surface (Levy et al. 1992; Shainberg et al. 1992), (4) controlling water runoff generation and displacement of soil layers (Smith et al. 1990; Bjorneberg and Aase 2000), (5) aiding in deposition of suspended particles and decreasing their settling time (Lentz and Sojka 1994), and (6) improving runoff water quality (Lentz et al. 1998; Sojka and

Entry 2000). These benefits of using PAM for structural stability of soil and aggregate formation are determined by complex alliance of polymer's properties (Sojka et al. 2007). Combining rock piece cover with polyacrylamide could help conserving water and soil (Tang and She 2018). Linear polyacrylamide has also been found effective for managing sodic soils which have dispersed soil/clay. Aggregation of dispersed sediments is one benefit which can be utilized for salty soils.

Cross-linked form of polyacrylamide has superabsorbent characteristics and thus can help in enhancing water-holding capacity, water use efficiency, soil permeability, infiltration rates, and plant performance (especially in soil with poor structure subjected to drought) and reducing compaction tendency and irrigation frequency. These benefits in soil can be helpful in countering salinity in soil. Having superabsorbent characteristics, polymer hydrogels greatly affect soil density, permeability, texture, structure, water evaporation, and water infiltration rates of the soil. The functional polymers were also used to enhance the efficiency of lower doses of pesticides and herbicides, thus protecting the environment indirectly by decreasing pollution load and in the cleanup of these pollutants (Ekebafe et al. 2011). Polymeric biocides and herbicides can help in reduction of water quality degradation by inhibiting nutrient leaching into water bodies or soil. Superabsorbent polymers are small crystalline structure and have the capacity to absorb water until equilibrium is reached, usually amounting to 200–500 times of their weight (Bhardwaj et al. 2007). When these polymers are mixed into a medium containing soil or something else, they hold on large amount of nutrients and water. These stored nutrients and water are released when plants need them. Thus, overall plant growth can be improved and water supply can be managed.

The use of PAM as a soil remedy depends on many factors, such as types of soils and the prevailing conditions in the fields (Mamedov et al. 2007; Al-Uzairy 2015). PAM applied in solution form was observed as more useful in regulating soil degradation than in the powdered form (Chao-Yin et al. 2012). Granular PAM with moderate and high molecular weight 2×10^5 Da and 1.2×10^7 Da, respectively, fused with phospho-gypsum at 4 Mg ha^{-1} also influence infiltration rate, erosion, and runoff (Mamedov et al. 2009). A moderate rate of PAM application (40 $Kgha^{-1}$) has therefore been recommended for soils with borderline salinity. Plant-derived polysaccharide, such as guar gum, poses no threats on aquatic organisms (Liu et al. 2014). It has the ability to combine with soil by forming clay flocs, thus reducing erosion and runoff (Lentz and Sojka 1994). The cationic polysaccharide, i.e., guar derivatives (molecular weight 0.2 to 2 million) effectively increased infiltration rate and reduced soil erosion (Ben-Hur et al. 1989; Agassi and Ben-Hur 1992). Water-soluble polymeric compounds have also been used largely for metal ions from various aqueous media. Extracellular polymeric substances (EPS) released by bacteria have also been successfully utilized in heavy metals removal and recovery by many researchers (Li and Yu 2014; Dobrowolski et al. 2017).

Biopolymers are derived from renewable sources and consist of natural materials (e.g., plant). Thus, their availability is not a problem as they can be developed at any period of time. In addition, these polymers are easily degradable in nature by microbial action and get transformed into water and carbon dioxide.

13.3.2 Engineered Nano-materials

Nanotechnology is creation, synthesis, design, as well as application of functional materials at the nanometer scale (1–100 nm). Nano-materials are very small in size, for example, smaller than 100 nanometers (nm). Though reclamation of sodic soil can be performed by adding gypsum ($CaSO_4.2H_2O$) in large quantities (10–20 t ha^{-1} of gypsum for improvement of top 20 cm soil), this reclaims only top 20 cm of soil and requires large amounts of water besides being a very slow process. The solubility of gypsum is only 0.25%. Nanotechnology can be used for synthesizing reclaimants that are more effective and easily manufactured. Sodicity is developed intrinsically by a feedback loop where Na^+ transport occurs via water flow through soil pores. Na^+ adheres to clay particles and damages the porous structure of the soil. For effective reclamation, Na^+ needs to be replaced by Ca^{2+}, and it requires some porous structure for removal, but it is no more available. Therefore, it is not just chemical reclaimant (like gypsum) which is required but also a measure to improve soil structure and porosity. A nano-reclaimant which would have nano-active principles along with polymeric carriers, and perhaps other additives, can be developed for more efficient reclamation and quick response. Nano-reclaimants containing polymeric carriers increase the stability of the soil via clay binding action (Bhardwaj et al. 2007, 2009, and 2010), and Na removal will be much quicker. Similarly, other nano-materials that may enhance the reclamation efficiency of salt-laden lands include nano-formulations of sulfur, zeolite substrates, and carbon manipulated at molecular level. The carbon and zeolite nanoparticles along with polymer carriers can also execute exchange sites for Na^+ binding and, therefore, decrease the efficiency of clay dispersion and swelling. Zeolites in agricultural industries have been incorporated as soil conditioners, remediation material for contaminated soil treatment, and slow-release fertilizers (Ming and Allen 2001). Nano-zeolites can be targeted to improve the soil quality of mined areas by expanding soil water-holding capacity, removing toxins, and improving nutrient levels. Development of suitable nanoparticles from crop residues such as biochar (pyrolyzed carbon) nano-materials can also boost the reclamation of sodic lands by improving structure and nutrient availability. Other examples of nanoparticles are zero-valent iron, iron sulfide, iron oxide, carbon nanotubes, and phosphate-based nanoparticles.

One of the most natural nanoparticles is soil colloid, which is composed of silicate containing clay minerals, aluminum/iron oxides/hydroxides, and organic matter. Engineered nanoparticles (ENPs) are those particles that are developed by man for specific nanotechnological properties. At the same time, understanding the behavior of nanoparticles in open environment, under the influence of water, organic surfaces, and biota, is also important to many ongoing soil processes connected with soil reclamation and plant nutrition.

Chitosan nanoparticles have also been used in agriculture for treatment of seeds and as biopesticide to fight off fungal infections. Nano-encapsulation of active ingredients also plays an important role in environmental protection by reducing evaporation and leaching of toxic substances. Tools, such as quantum dots, have been applied in the areas of plant pathology for regular monitoring of beneficial organisms as well as pathogens (Levesque 2001). The modern nanotechnology also involves development of materials that are readily assimilated by microorganisms, posing no threats to the environment. Such nanoparticles show positive effects on efficiency of seed germination and accumulation of vegetative biomass in seedlings and development of shoot and root formation. Nanoparticles can show their effect at the cell level and increase the physiological processes in plants. Certain nanoparticles, e.g., nanoparticles of zinc (Zn), iron (Fe), cuprum, etc., are approximately 40 times less harmful. Their ionic forms can get involved in the biochemical reactions and in electron transfer and, therefore, promote the transformation of nitrates to ammonia, enhance plant enzymes activity, synthesize amino acids and enzymes, intensify plant respiration, and increase nitrogen and carbon nutrition. Since nanoparticles can interact with things at molecular level, caution should be exercised, and interactions should be studied with precision. ZnO and CuO nanoparticles can alter important processes like metabolism of microorganisms and plants, and these changes may be beneficial or detrimental. The nanotechnology may contribute substantially if we have knowledge of plant-microbe associations. In chickpea plants, the catalase activity in the colloidal solution of molybdenum nanoparticles in a variety of concentrations increased the efficiency of nitrogenase enzyme by twofold over the control. Other engineered nano-materials having properties in the reclamation of salt from water and soil are nano-catalysts; nano-sorbents; redox-active nanoparticles; nanostructured, reactive membranes; and bio-active nanoparticles (Luca and Ferrer 2017). Plant grown in salt-affected soils most often suffers from deficiencies of nutrients. Most nutrients are invariable in salty conditions. Of the applied fertilizer, around 40–70%, 80–90%, and 50–70% of N, P, and K were lost in a manner that contributes to environmental pollution. However, nano-encapsulated fertilizers, both herbicides and pesticides, help in gradual release of agrochemicals and nutrients which results in maintained dosage to the plants.

Nano-oxides improve chlorophyll content, antioxidant enzyme activity, grain yield, etc. and, therefore, increase wheat yield under saline condition (Babaei et al. 2017). In addition, nanotechnology can play a key role in sensors application. Biosensors help in pesticide detection in many crops and serve as a support structure for crop commodity market (Duhan et al. 2017). Fullerene, a carbon nano-material, is capable of adsorbing various inorganic and organic compounds, namely, amino acids, vitamins, and minerals existing in the soil. Tong et al. (2007) observed that implementation of fullerene nanoparticles did not influence bacterial diversity in the soil. Nyberg et al. (2008) found that fullerene nanoparticles (C60) had no effect on anaerobic microorganisms. At the same time, there are also reports of negative interaction of nano-materials with microbial communities and processes, but interactions are always material and working environment specific. Overall, nanotechnology holds huge prospects for development of materials for efficiently managing salt-laden soils as well as waters.

13.4 Conclusion

Salt-laden soils and salty water use in agriculture poses challenges which are difficult to counter with conventional approaches. Challenges exist in seed germination, nutrient availability, drainage, and irrigation and most importantly in establishing plant stand. Therefore, possibilities for engineered efficient materials using nanotechnology and polymer science are immense. Nano-materials can be more energy efficient and resource conserving and can be targeted for precision applications. Doors are wide open for developing new materials and new methods of application of customized tools for soil improvement, better crop production, and other specific uses.

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Potential Pollutants in Soil System: Impacts and Remediation

14

Manasvini and Khajanchi Lal

Abstract

The economic upswing of the developing countries propelled the agricultural and industrial growth which has resulted in serious environmental degradation. All the ecosystems of earth are equally facing the problems caused by different types of pollutants. In our day-to-day life, we are exposed to various kinds of pollutants. We often talk about water and air pollution but soil pollution is very less discussed and reported. Soil have been carrying in itself number of contaminants mainly heavy metals, pesticides, organophosphates and radioactive residues from thousands of years acting as a sink of pollutants. These accumulated contaminants cause various types of health issues and affect other life forms. Any kind of imbalance causes visible changes not only in soil ecosystem but also in air, water and biological life. Once it degrades it is very difficult to reclaim it fully in its natural form. This chapter is an outcome of reading various works of literature regarding soil pollution, its possible causes and effects on life forms, various types of pollutants and the bioavailability of these contaminants. The chapter at the end is closed by discussing various strategies for the remediation of the contaminated soil.

Keywords

Bioremediation · Contamination · Heavy metals · Pollutants · Soil pollution · Organophosphates

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14.1 Introduction

Severe contamination of soil with pollutants which poses serious threat to human, animals, plants or ecosystem health is known as soil pollution. Soil pollution occurs due to increase of any chemical, elements or nutrients in the soil which is higher than a normal concentration, as a result of anthropogenic or natural factors which leads to undesirable changes in physical, chemical and biological properties of soil. Contamination of soil can occur by natural sources, but some manmade practices like agriculture and industrial activities are major contributors. Other pollutants responsible for soil pollution are leaching of wastes from landfills, hazardous waste, percolation of contaminated water in the soil and different types of chemicals used in day-to-day life or by the industries. These contaminants can occur on the site itself or may be carried by the movement of groundwater and soil water.

14.2 Causes of Soil Pollution

Several natural events cause infiltrations of chemicals or other elements in soil. Volcanic eruptions are the major natural cause of introduction of dioxin like compounds in the soil (Deardorff et al. 2008). Forest fires result in high levels of polycyclic aromatic hydrocarbon level in forest soil (Kim et al. 2011). Weathering of soil causes accumulation of heavy metals in soil. Wang et al. (2017) identified the distribution of Cu, Pb, Cd, Zn and Cr in the soils of Three Gorges Reservoir, China, which he explained was the result of rock weathering. Similarly, Javied et al. (2009*)* found out that weathering of phosphate rocks results in heavy metal pollution of soil. Acid rain is also a global concern of soil pollution. It not only effects the pH of the soil but also enhances the metal toxicity (Rais 2005).

There have always been anthropogenic pressures on earth as a result of which pollution has ever been a burden from the starting of human evolution (Rhind 2009). However, the quantity of contaminants present keeps on increasing with passing time. The chief sources for the contaminations of soil with different types of chemicals and elements are industries, agricultural practices and poor waste disposal practices. India is a country where agriculture sector is the most important part of Indian economy. About 58% of India's population is involved in farming for their livelihood and income. Moreover, the increasing population of India demands for more food. To achieve the goal of increased yield of crop, various types of agrochemicals are used ultimately leading to soil pollution. The industrial sector of India is also emerging rapidly. Introduction of industrial units in any area means direct contamination of soil with the harmful chemicals and elements. They are having inappropriate waste disposal facilities and ETPs with insufficient capacities. Moreover, most of their waste material is dumped on land in unlawful manner. Different types of industries contribute to soil pollution by dumping heavy metals, hydrocarbons, nuclear waste, etc. Similarly, municipal and domestic waste which is produced in enormous amount by the dwellers of the city has long-term impacts on the environment. The most known causes of the soil pollutants are presented in Table 14.1.

Table 14.1 Natural and anthropogenic factors responsible for soil pollution

Natural pollutants	Anthropogenic pollutants
Natural accumulation of minerals	Acid rain
Production of salts	Use of chemicals in agriculture
Volcanic eruptions	Poor waste disposal habits
Forest fires	Oil leakage
	Mining activities
	Industrial activities
	Construction
	Leakage of sewers and pipelines
	Fuel leakage from automobiles
	Faecal matter
	Waste land filling
	Chemical disposal
	Nuclear waste disposal

14.3 Types of Soil Pollutants

For the improvement in the quality of life and making it comfortable, humans have done various inventions. Though these inventions have proved to be useful for us, these also have serious impacts on human health as well as environment. There are many anthropogenic activities like agriculture, industries, mining, ore smelting, burning of fossil fuels, etc., generating many types of chemicals and toxic substances which end up depositing in the soil. These chemicals persist in nature for a long time and amplify by entering into food chain. The types of pollutants causing soil pollution are presented in Table 14.2.

14.3.1 Heavy Metals as Pollutants

There are several elements found responsible for the contamination of the soil, e.g. Pb, Cd, Cu, Ni, Zn, Se, Hg, etc. These contaminants affect the production of plants and also enter our food chain consequently affecting our health. They bioaccumulate and their concentration also increases with time due to biomagnifications in soil. These contaminants are rapidly adsorbed first followed by slow adsorption reactions. In order of abundance, the elements found in the contaminated sites are Pb, Cr, As, Zn, Cd, Cu, Hg and Ni.

Lead is generally present in the soil in the form of ionic lead Pb (II), lead oxides and hydroxides and lead metal oxyanions. Anionic lead and lead hydroxyl are the reactive forms. Lead is generally present in the leafy vegetables and hardly taken by the fruits.

Table 14.2 Types of pollutants causing soil pollution

Metals	Sources of pollution	Effects on human health
Inorganic pollutants of soil		
Aluminium (Al)	Mining, manufacturing industry, industrial waste disposal	Neurological diseases
Arsenic (As)	Arsenical pesticides, mining and smelting, wood preservatives, combustion of coal, pharmacy industries, glass industry, leather preservatives, electronics industry, arsenic-contaminated drinking water	Arsenicosis, neurological disease, gastrointestinal and liver damage, bone marrow and blood disease, hair and nail disease, cardiovascular diseases
Cadmium (Cd)	Paint and electroplating industry, solar cells, phosphate fertilizers, batteries, sewage sludge, PVC, mining, burning of coal, tyres, plastic, motor oils	Low bone density, osteomalacia, kidney and liver damage, itai-itai disease
Chromium (Cr)	Leather and tannery industry, paints, ceramics, photography and wood preservatives	Dermatitis, skin allergy
Copper(Cu)	Industries producing non-ferrous metal, wood combustion, iron-steel production, Bordeaux (fungicide)	Gastrointestinal problems (15–75 mg Cu)
Fluoride (F)	Agrochemicals aluminium industry, steel production plants, superphosphate plants, ceramic factories, coal-burning power plants, brickworks, glassworks and oil refineries	Skeletal fluorosis, crippling and pains in joints, bone deformities, calcification of tendons and ligaments
Lead (Pb)	Pottery alloys, pipe manufacturing, paints, varnishes, pesticides, plastic industry, batteries, solder, ammunition, pigments, hair colour, mining, plumbing	Loss of weight and teeth, blue line in gums, anaemia, neurological damage, encephalopathy, bone deterioration, hypertension, kidney disease
Mercury (Hg)	Electronic industry, plastic manufacturing unit, thermometer, dental filling, pesticides, medical waste, mining, coal and fuel burning	Damage to central nervous system, damage to gastric system, organo-mercuric compounds accumulate in brain causing lower IQ, teratogenic, causes heart disease, affects eyesight and sense of touch
Nickel (Ni)	Steel and electroplating industries, making alloys	Chronic bronchitis, hand eczema, inhalation of dust causes asthma attack
Selenium (Se)	Fossil fuel burning, solid waste disposal by coal firing power plants, fly ash	Effects central nervous system and heart and causes dysfunction of lungs
Zinc (Zn)	Zinc ore smelting, refuse of municipality and automobiles, biosolids	Mental fume fever (at 15 mg/m^3 in air)

(continued)

Table 14.2 (continued)

Metals	Sources of pollution	Effects on human health
Organic pollutants of soil		
Organic pesticides	Chlorinated hydrocarbons, organophosphates and carbamates used in agriculture, public health, industry and home application	Accumulate in fatty tissues of animals, enters food chain
Plant waste	Fallen leaves, twigs and other plant parts	
Animal waste (bacteria, fungus, viruses and protozoa)	Human and animal excreta, dead bodies	
Radioactive pollutants		
^{40}K, ^{238}U, ^{232}Th, ^{90}Sr, ^{137}Cs, ^{134}Cs, ^{239}Pu, ^{14}C	Atmospheric nuclear weapon, nuclear accidents, nuclear testing, mineral fertilizers, mining of radioactive ores	Enters into food chain, alters genetic structure, short-term exposure causes sickness, tissue damage and hair loss

Source: Brevik and Burgess (2013) and Singh et al. (2006)
US Agency for Toxic Substances and Disease Registry (website): www.atsdr.cdc.gov

The second abundant heavy metal is chromium which doesn't occur naturally in the elemental form. It is found in the soil as compound of chromate and dichromate. Cr (IV) is dominant compound in soil which is toxic and mobile in nature. It is very toxic to plants and its leachability increases at higher pH values.

Arsenic is the third most abundant contaminant in soil. As in compound form adsorbs very tightly to the soil particles. In the aerobic conditions, As is found in dominance as arsenate. Arsenate when comes in contact with any metal precipitates very fast. In the reducing condition, As occurs as arsenite which when comes in contact with any metal co-precipitates with sulphur compound.

Cd as the following abundant contaminant is found as the divalent compound. It is highly persistent in nature and can remain in there for many years. Even very low concentration of this metal proves to be highly dangerous to plant's life. This metal, like Cr, accumulates in the tissues of leafy vegetables but not in the fruits. pH, presence of fertilizers and heavy metals affects the uptake of Cd by the plants.

Cu is an essential micronutrient which is very vital for the growth of the plants as well as animals. After entering into the environment, it rapidly gets stable. This element is not magnified or accumulated in the food chain. In soil Cu is mostly present as an organic complex. Only a small amount of it is present as ionic Cu (II).

Mercury generally occurs as mercuric, mercurous or alkylated form. The stability of mercury depends upon the pH and redox potential. It is highly toxic in the alkylated form which is both soluble and volatile. However, mercurous and mercuric forms are stable at oxidizing conditions. Mercury is adsorbed by the soil at high pH.

Ni is present in the environment at a very low level and it is very essential. But when its concentration increases, it can be very dangerous. Ni is highly stable at alkaline pH and form precipitates of hydroxides of Ni which dissolves at acidic conditions. In highly alkaline conditions, it forms nickelite ions which are highly soluble.

14.3.2 Pesticides as Pollutants

Pesticides are commonly used for the control of pests in agricultural farms to alleviate the yield of crops. There are more than 500 types of pesticides which are being used in agriculture. These pesticides are divided into three types: (i) chlorinated hydrocarbons like DDT, DDE, DDD, aldrin, dieldrin, etc.; (ii) carbamates like aldicarb, carbaryl, etc.; and (iii) organophosphates like malathion, parathion, diazinon, etc. Once these pesticides are used in agriculture or other purposes, they enter into the environment through various methods. Pesticides which are soluble in water leach into the groundwater by soil. Pesticides with high vapour pressure tend to enter into the atmosphere by gaseous diffusion, while in soil they get sorbed by the soil particles and organic matter.

Although pesticides persist for a long period of time, soil plays an important role for the degradation of pesticides by chemical or microbial reactions. Microbes or other organisms present in soil changes the pesticides into less persistent form. Sometimes pesticides in the soil get degraded by the absorption of light from the soil particles. Once the light is adsorbed by the soil molecule, they get excited and produce a degraded byproduct. The process is known as photochemical degradation.

14.3.3 Radioactive Materials as Pollutants

In soil the radioactive material is deposited by the testing of nuclear weapons, nuclear explosion or accidents in power plants. The soil which is contaminated by the radionuclides effects the human and plant health for a long period of time by entering into the food chains. Major radionuclides which have been proved harmful for the soil health are tabulated in Table 14.3.

The fate of radionuclide particles in soil depends upon many factors such as climatic factor, physiochemical factors of the soil and the flora present on that soil. These radionuclides may also be taken by the plants or can be migrated to other places.

14.4 Bioavailability of Pollutants in Soil

Once the pollutant is introduced into the soil, it interacts with the solid phase of the soil through the process of sorption, desorption, dissolution or precipitation process. Once taken by the plants, these isotopes travel the food chain and effects animals and plants life. The chemicals released from the soil enter into the pores of the soil and

Table 14.3 Radioactive isotopes and their half-life

Isotope	Half-life (in years)
^{90}Sr	28
^{134}Cs	2
^{137}Cs	30
^{14}C	5.7×10^{3}
^{40}K	1.3×10^{9}
^{239}Pu	2.4×10^{4}
^{232}Th	1.4×10^{10}
^{226}Ra	1600
^{210}Pb	22.3
^{238}U	4.5×109
^{241}Am	432.2

interacts with the solid surface of the soil by forming bonds. These contaminants which are present as the solution in the soil pores are most bioavailable form. However, bioavailability of any contaminants also depends on some other physical and chemical characteristics of soil.

14.4.1 Fate of Inorganic Contaminants in Soil

1. *pH*: pH is the most important parameter which determines the concentration of metals in soil solution. If the pH is high (alkaline), there are chances of less metals present in the soil. Low pH of soil favours the availability of higher concentration of metals in the soil. Naidu et al. (1997) found out that at low pH metals are more bioavailable due to formation of free ionic species or as soluble organometals. On the other hand, at higher pH the metals generally form metal minerals phosphates and carbonates which are insoluble in nature. Yong et al. (1993) illustrated that decrease in the concentration of the metal ions in solution occurs due to adsorption in the acidic condition, while in the basic condition, the main factor for the decrease in the metal concentration is due to the precipitation process. At the neutral pH, complexation process takes place.
2. *Organic matter*: Metals are more prone to bind with the organic matter of the soil in solid as well as solution phase. Thus, the amount of organic matter governs the bioavailability of the metals in the soil. The organic matter of the soil is comprised of humic and non humic substances. The humic substances are made up of humic acid, fulvic acid and the humans. These substances are decomposed at its best and cannot decompose further. The organic matter retains the metals by forming complexes or by the adsorption process. These metals are retained by the organic matter by the negatively charged particles present on it. Increase in these negatively charged particles occur during the humification process.
3. *Redox potential*: Redox is the process in which flow of electrons takes place from a reducing agent to an oxidizing agent. This process is considered to be very slow in soils. This process is controlled by the aqueous free electron which is denoted as pE. Soil which is dry and well aerated has high pE value. On the other hand, the

soil which is rich in organic matter has very low pE value. Low pE values are considered to be good for the solubility of the metals.

4. *Clay content and soil texture*: Clay adsorb the heavy metal ions through the ion exchange process or by the specific adsorption. The metal ions are adsorbed on the surface of the clay particle by forming a bond with the pre-adsorbed hydroxyl ion. Adsorption may also occur on the sites which are created by the proton removal. The soil with more fraction of clay tends to adsorb more metals than other types of soil. Clay tends to arrest more metal ions than any other type of soil. Thus, clay minerals and the texture determine the mobility of the heavy metals between the solid and the liquid phases of soil which has direct effect on the metal bioavailability of plants.
5. *Oxides of iron and manganese*: Hydrous ferrous which are present as the coating on phyllosilicates and as free gels and crystals influence metal solubility in the oxidizing environment. They reduce the concentration of metals from the soil either by precipitation or by specific adsorption. However, oxides of manganese adsorb heavy metals more strongly than the ferrous oxides. For the solubility of Pb, Zn, Cd and Cu, both the oxides proved to be a major component.

14.4.2 Fate of Organic Contaminants in Soil

1. *Adsorption/desorption*: The adsorption of the organic compounds in the active sites of any adsorbent arrests the mobility of the contaminants in the soil. The organic contaminants with high solubility has more potential for bioavailability than the insoluble contaminants.
2. *Biodegradation*: Biodegradation is the prime factor for the reduction of organic contaminants from the soil. Different types of microbial flora and fauna increase the solubility of the organic contaminants. However, the time needed for the biodegradation of these contaminants differs according to the chemical characteristic of the pollutants, e.g. the organochlorinated compounds have very low leaching potential and are persistent in nature contrary to the monocyclic aromatic hydrocarbons, some chlorobenzenes, short-chain aliphatic compounds and phenols which degrade very fast and hence leach very rapidly. Polycyclic aromatic hydrocarbons and phenols are also degraded by photolysis, hydrolysis and oxidation.

14.5 Bioindicators of Soil Pollution

Bioindicators are living organism species or group of species (communities) which give an idea of the quality of the environment in which they exist. They alter their vital processes in the polluting surrounding which shows their sensitivity towards pollutants (Singh et al. 2006). Various types of nematodes, invertebrates, tree seedlings, fungi and microorganism show their changed behaviour in the polluted soil. Some of the examples of bioindicators are given in Table 14.4.

Table 14.4 Different bioindicator species of soil pollution

Species	Pollutant	Reference
Rhinocricus padbergi	PAH	Souza and Fontanetti (2011)
Allolobophora caliginosa	Dioxin	Reinecke and Nash (1984)
Lumbricus rubellus	Dioxin	
Eicchornia crassipes	Fe	Akagha et al. (2017)
Pteris vittata	As	Gumaelius et al. (2004)
Xanthoria candelaria	Cd, Pb	Aslan et al. (2011)
Ramalina polymorpha	Se	
Lecanora muralis	Ni	
Amanita muscaria	Cd, Pb, Zn	Mazur et al. (2015)
Plantago major	Cd, Pb	
Urtica dioica	Cu	Malizia et al. (2012)
Taraxacum officinale	Cu	
Trifolium pratense	Pb	
Miconia lutescens	As	Bech et al. (1997)
Bidens cynapiifolia	As	
Alyssum bertolonii	Ni	Brooks and Radford (1978)

14.6 Remedial Measures for Polluted Soil

14.6.1 Physico-chemical Remediation

The simplest method of soil remediation is replacing the contaminated soil with the clean soil. However, it can only be done only if the extent of contamination is known. The extraction of soil can be done by using bulldozers and diggers. This process of excavation is costly. The contaminated soil can also be separated by the use of magnetic and gravitational separation or cyclones. Sometimes the contaminated soil is insulated by making protective cover which comprises of four layers: (i) plant layer to control the erosion of soil, (ii) a drainage layer to drain off the rain water, (iii) a nonpermeable layer to protect the contaminated area with rain water and (iv) a base layer of suitable material. Decontamination of soil can also be done by employing the process of electro-remediation in which the electrodes are inserted into the ground on the opposite site. As a result, the charged particles migrate towards the electric field. Washing of soil with water is another method but it is more suitable for the granular soils. Chemical washing is usually practised to remove the contaminants adsorbed on the surface of the soil, and both physical-chemical methods of decontamination of soil are pricier than the bioremediation practices (Soleimani and Jaber 2014). Soil vapour extraction or air-sparging technique is used to reclaim VOCs from soil (Watson 1996). Streche et al. (2018) remediate the soil artificially contaminated by hydrocarbons by adding diesel and determined the degree of the removal of the pollutants from soil over time by using electrochemical technique.

14.6.2 Thermal Remediation

The thermal process in which soil is melt by providing high electrical heating by inserting graphite electrode in soil is termed as vitrification. In this process metals are fused with silica at very high temperature to form inert glass, thus making the metals immovable.

14.6.3 Bioremediation

Bioremediation is a cost-effective process in which the contaminants are converted into a non-toxic or less toxic form by the use of any living organism, e.g. plants, fungi, yeast or bacteria. Depending upon the site of treatment, the bioremediation process can be divided into *in situ* and *ex situ*. In *in situ* remediation, the treatment takes place on original site of the soil, while *ex situ* bioremediation involves excavation of the soil from its original site and then treating it. Various types of exotic and genetically modified organisms are used to sequester the contaminants in soil. But use of plants is much easy approach for removal of contaminants by plant uptake. In situ methods include phytostabilization, phytoimmobilization, phytovolatilization, phytoextraction, phytodegradation and rhizofiltration.

Phytostabilization is a very promising remedial technology in which the mobility of the contaminants in soil is being arrested. This method involves different types of process which are carried out by the living organism during its growth period. The process reduces leaching of metal in soil by converting it into insoluble oxidation state. The plants behave differently with different metals. They can stabilize some metals and can also behave as a good accumulator for others. Some plant species are very good adapters to survive under the highly polluted conditions in soil and thus known as hyperaccumulators. Different species of plants have different accumulation capability, bioaccumulation factor and translocation factor. Madejon et al. (2017) found that the naturally occurring woody species of *Eucalyptus camaldulensis* in Guadiamar valley of Australia is good for phyto-stabilization of As and Pb in soil but phytoextracted Mn and Zn. In phytoextraction the plants accumulate the contaminants in plant parts and reduce them into less toxic forms by their metabolic processes. Plants used for phytoextraction should grow quickly and have a high production of biomass. Indian mustard is gaining popularity for this remedial method. Generally, the plants with a heavy root system which can transport the pollutants easily to the leaves are used for this purpose. Plants used for phytoextraction produce chelating agents which speed up the process of transportation and accumulation of contaminants in plant parts (Ali et al. 2013).

Phytovolatilization, on the other hand, releases the contaminants into the atmosphere through leaves after converting them into gaseous form. This method has least effect on soil and thus is highly recommended for the decontamination of polluted land. Some of the plant species known for the removal of pollutants from the soil are enlisted in Table 14.5.

Table 14.5 Different plant species used for phytoremediation of polluted soil

Species	Pollutant	Reference
Brassica nigra	Cd, Mn, Ni, Cu, Fe and Zn	Singh et al. (2015)
Thlaspi caerulescens	Zn, Cd	Frey et al. (2000) and Uneo et al. (2004)
Typha domingensis	Pb, Ni and Cd	Mojiri et al. (2013)
Thlaspi goesingense	Ni, Zn	Prasad and Freitas (2003)
Thlaspi ochroleucum	Ni, Zn	
Thlaspi rotundifolium	Ni, Zn,Pb	
Nicotiana tabacum	Cd	Yang et al. (2017)
Ipomoea alpina	Cu	Baker and Walker (1990)
Thlaspi caerulescens	Zn, Cd	Reeves and Brooks(1983) and Baker and Walker (1990)
Sebertia acuminata	Ni	Jaffre et al. (1976)
Helianthus annuus, *Tithonia diversifolia*	Pb, Zn	Adesodun et al. (2010)
Solanum nigrum	Cd	Ji et al. (2011)
Thlaspi caerulescens, *Brassica* spp.	Cd	Ebbs et al. (1997)
Brassica campestris, *Solanum nigrum*, *Triticum aestivum*	Cd, Cr, Cu, Fe, Mn, Ni, Pb and Zn	Singh et al. (2010)
Ricinus communis, *Colocasia esculenta*, *Polygonum chinense*	Cu, Pb and Zn	Xiaohai et al. (2008)
Cynodon dactylon, *Dactyloctenium aegyptium*, *Xanthium strumarium*, *Cannabis sativa*, *Chenopodium album*	Cr, Cu, Co, Ni, Pb and Zn	Malik et al. (2010)
Trifolium alexandrinum	Cr, Cu, Cd, Co and Pb	Bhatti et al. (2016)
Pennisetum glaucum, *Vetiveria zizanioides*, *Paspalum notatum*	Pb, Cd	Xia (2004)

14.7 Micro-remediation

Microbial remediation of pollutants from the soil is very efficient and environmental friendly technique to decontaminate the soil from different types of pollutants. Various advancements have made in the techniques of microbial remediation of pollutants. However, the process of bioremediation markedly varies with metal as well as the microorganisms. In microbial remediation the metals are immobilized to reduce the bioavailability and mobility and remove the metal from the soil. Bio-stimulation (stimulation of viable native microbial population), bioaccumulation (use of live cells), biosorption (use of dead microbial biomass) and bioaugmentation (ratification introduction of viable population) are some of the methods for the effective removal of metals from the contaminated soil. Table 14.6 is enlisted with few examples of microbial species which are proved to be useful for micro-remediation of different types of organic and inorganic pollutants from the contaminated soil.

Table 14.6 Different microorganisms used in microbial remediation of polluted soil

Species	Pollutant	Reference
Pseudomonas aeruginosa, *Chlorella vulgaris*, *Phormidium valderium*	Ni	Chatterjee et al. (2008)
Stereum hirsutum, *Citrobacter* sp., *Chlorella vulgaris*, *Ganoderma applanatum*, *Volvariella volvacea*, *Daedalea quercina*	Pb	Chatterjee et al. (2008)
Desulfovibrio vulgaris, *Desulfuromonas*, *Acetoxidans*, *Desulfovibrio*, *Fructosovorans*	Cr	Chatterjee et al. (2008)
Ganoderma applanatum, *Zooglea* sp., *Citrobacter* sp., *Aspergillus niger*, *Pleurotus ostreatus*, *Stereum hirsutum*, *Phormidium valderium*	Cd	Chatterjee et al. (2008)
Bacillus sp., *Chlorella vulgaris*, *Aspergillus niger*, *Pleurotus ostreatus*, *Daedalea quercina*	Zn	Chatterjee et al. (2008)
Bacillus sp., *Pseudomonas aeruginosa*, *Chlorella vulgaris*, *Pleurotus ostreatus*, *Phormidium valderium*, *Volvariella volvacea*, *Daedalea quercina*	Cu	Chatterjee et al. (2008)
Zooglea sp., *Phormidium valderium*	Co	Chatterjee et al. (2008)
Chlorella vulgaris , *Rhizopus arrhizus*, *Volvariella volvacea Geobacter metallireducens*	Hg	Chatterjee et al. (2008)
Organophosphates		
Enterobacter sp., *Erwinia* sp., *Streptococcus* sp., *Pseudomonas aeruginosa*, *Acinetobacter* sp., *Arthrobacter* sp.	Malathion	Mohapatra (2008)
Erwinia carotovora sp., *Pseudomonas* sp., *Pseudomonas aeruginosa*, *Pseudomonas diminutum*, *Pseudomonas melophthora*	Diazinon	Mohapatra (2008)
Nocardia sp., *Proteus vulgaris*, *Xanthomonas* sp., *Rhizobium* sp., *Pseudomonas* sp., *Pseudomonas diminutum*	Dimethonate	Mohapatra (2008)
Explosives		
Enterobacteria, *Escherichia coli*, *Clostridium*, *Acetylbutilecum*, *Aspergillus niger*, *Klebsiella pneumoniae*, *Clostridium bifermentans*, *Rhodococcus rhodochrous*	RDX	Adrian and Arnett (2007) and Crocker et al. (2006)
Methylobacterium, *Klebsiella pneumoniae*, *Clostridium bifermentans*	HMX	Adrian and Arnett (2007) and Crocker et al. (2006)
Phanerochaete chrysosporium, *Clostridium* sp.	CL-20	Adrian and Arnett (2007) and Crocker et al. (2006)
Pseudomonas, *Phanerochaete chrysosporium*, *Mycobacterium*, *Rhodococcus erythropolis*, *Clostridium* sp.	TNT	Adrian and Arnett (2007)

14.8 Vermiremediation

Presence of microbes is the indicator of soil health. Higher number of microbes indicates presence of higher amount of nutrients in soil. Earthworms are used to increase the number of earthworms by creating favourable conditions and triggering the microbial activities (Dabke 2013). In parallel introduction of worms in the soil is also used for the decontamination of the polluted soil. This technique is known as vermiremediation, used to sequester heavy metals (Sim et al. 2012), polycyclic aromatic hydrocarbons (PAH) (Rorat et al. 2017), petroleum hydrocarbons (Kelechi et al. 2016), fly ash (Saxena et al. 1998) and human excreta (Bajsa et al. 2004).

Different earthworm species used for vermiremediation of soil are *Lumbricus rubellus*, *Lumbricus terrestris*, *Eisenia fetida*, *Perionyx excavatus*, *Metaphire posthuma*, *Hyperiodrilus africanus*, *Aporrectodea tuberculata*, *Dendrobaena rubida*, *Dendrobaena veneta*, *Eiseniella tetraedra* and *Allolobophora chlorotica.*

14.9 Conclusions

Soil is considered as the major factor of the environment which lays the foundation of life on earth. If polluted it can disturb the other life forms and will not be able to provide its best services to us. Contamination of food grown on the polluted land will result into the introduction of contaminants in our food chain which can severely affect human health. Soil may become polluted from the ever-expanding activities leading to development or by certain natural phenomenon. Either of the case, in both ways the life is at the losing end. In today's time we cannot stop thinking about the idea of development but can develop new methods for the remediation of soil. We also have come up with so many techniques to remediate it. These remediation techniques are being used to reduce the associated risks and to make the land available for further use. Many conventional and nonconventional methods are in practice, but bioremediation technique is proved to be the best known method for soil remediation so far as it's less expensive and almost natural contrary to chemical and physical methods. It is important to focus on the biological methods of remediation like phytoremediation, vermiremediation or microbial remediation so that further chemical or physical disturbances should be avoided with the soil.

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Groundwater Pollution Through Different Contaminants: Indian Scenario

15

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Abstract

The groundwater has emerged as major reliable source for agriculture as more than 60% of irrigated agriculture and 85% of drinking water supplies are dependent on groundwater. Round-the-clock water availability at the point of use, less conveyance losses, judicious water use and less cost of pumping are the major reasons behind the increased pumping of groundwater irrigation, but declining quality of groundwater has been becoming an issue of a concern, and it can be attributed to water contamination and/or over-exploitation. The contamination is taking place through various sources and pathways like anthropogenic (agricultural, industrial and domestic) and natural (geogenic/pedogenic origin) reasons. The basic cause behind drastic decline in groundwater quality is lack of appropriate rules and regulations, but off late to protect groundwater and take safeguards against over-exploitation, Government of India, in 1970, framed a Model Groundwater (Control and Regulation) Bill for adoption by the states and later on in the year 2013 started Atal Bhujal Yojana (ABHY) which focuses on interventions to improve groundwater quality. The main parameters that are considered to assess the contamination of groundwater by CGWB are salinity level; concentrations of fluoride, nitrate, arsenic and iron; and concentration of heavy metals like lead, chromium and cadmium, and the groundwater of most of the states of India like Punjab, Haryana, Uttar Pradesh, West Bengal, Tamil Nadu and Telangana was found to be contaminated by all these elements. Iron was found to be major contaminant in most of the states followed by fluoride, nitrate, arsenic, salinity and lead contamination. The indicators like pH, TDS, BOD and COD and metals like Cr, Cd, Ni, Zn, Cu, Pb, etc. are measured to know the extent of contamination. Sizable area in the vicinity of industrial sites is found contaminated by different kinds of contaminants that are elaborated in the text

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with level of concentration occurring in soil, plant as well as groundwater. The heavy metal pollution index was calculated to measure the overall quality of groundwater in the Ankleshwar Industrial Estate of Gujarat in India. Various techniques for remediating the contaminated groundwater are also discussed.

Keywords

Groundwater contamination · Pollutant · Heavy metals · Heavy metal pollution index · Nitrate pollution

15.1 Introduction

As per the estimates of National Commission for Integrated Water Resources Development (NCIWRD), the total water utilization of India in the year 2010 was 710 billion cubic metre (BCM), and it is estimated to rise to 1180 BCM in 2050 for high projection scenario (CWC 2014). The average annual per capita water availability of the country was assessed to 1544 cubic metres in the year 2011 which may reduce further to 1341 and 1140 in 2025 and 2050, respectively (CWC 2015). India has monsoonal climate, and rainfall received during monsoon had been reliable source of water to fulfil the huge water demand of the country. However, vagaries in Indian monsoon have led rainfall a no more reliable source of water, and thus, the other dependable water resources are needed to be explored to meet water demand of the country for drinking, domestic and agricultural purposes. The groundwater has emerged as major reliable source for agriculture as more than 60% of irrigated agriculture and 85% of drinking water supplies are dependent on groundwater. India is the largest user of groundwater in the world with an estimated 253 BCM of groundwater withdrawal per year which is over a quarter of the global total. The total annual replenishable groundwater resources of the country are 447 BCM, and out of which 411 BCM is net annual available groundwater used for developmental purposes. The stage of groundwater development of India is 62%, and about 90% of annual groundwater withdrawal is for irrigation purposes (CGWB 2017a). Round-the-clock water availability at the point of use, less conveyance losses, judicious water use and less cost of pumping are the major reasons behind the increased pumping of groundwater irrigation. However declining quality of groundwater has been becoming an issue of a concern, and it can be attributed to water contamination, over-exploitation or combination of the two. The contamination is taking place through various sources and pathways like anthropogenic (agricultural, industrial and domestic) and natural (geogenic/pedogenic origin). The over-exploitation of groundwater has resulted in saline water intrusion in the coastal areas. Out of total 6584 assessed units (Blocks/Mandals/Firka/Talukas) of the country by Central Ground Water Board (CGWB) about 2/3 of the units (numbering 4520) were found to be safe, whereas 1034 over-exploited (stage of groundwater development is more than 100%), 253 critical (stage of groundwater development is 90–100%), 96 salines and 681 semi-critical (stage of groundwater development is 70–100%)

blocks (CGWB 2017b). With nearly 70% of water being contaminated, India is placed at 120th position among 122 countries in the water quality index. When it comes to the groundwater, about 60% of districts in the country have water quality problem because of either contamination or depletion or both. About 54% of India's groundwater wells are declining, and 21 major cities are expected to run out of groundwater by 2020, affecting nearly 100 million people (NITI Aayog 2018).

15.1.1 Contamination Versus Pollution in Groundwater

Contamination is the occurrence of an unwanted constituent or impurity in a material, physical body, natural environment, workplace, etc. Pollution is the existence or introduction into the environment of a substance which has harmful or poisonous effects.

Pollution is contamination that results in or can result in adverse biological effects to resident communities. Contamination turns into pollution when they are having harmful effects on the resident communities. All pollutants can be called contaminants, but not all contaminants are pollutants. The hazardous effect of contamination cannot be predicted in laboratory alone, but toxicity tests at field level and that of resident communities are also needed to be carried out.

15.1.2 Government Policies to Prevent Groundwater Pollution in India

The main reason behind drastic decline in groundwater quality is lack of appropriate rules and regulations. The groundwater laws were not in place in India until 1970, whereas the laws prepared afterwards were not enforced at national level, and state government was given responsibilities to implement them. To protect groundwater and take safeguards against over-exploitation, Government of India, in 1970, framed a Model Groundwater (Control and Regulation) Bill for adoption by the states. It was subsequently revised in 1972, 1996 and 2005 to provide the framework to regulate indiscriminate extraction of groundwater. It enabled the states to enact groundwater legislation, a Model Bill to regulate and control development of groundwater that has been circulated by the Ministry of Water Resources to all the states/UTs. However, only 15 states/UTs have adopted and implemented the groundwater legislation on the lines of Model Bill (MoWR). The principles of decentralization and participatory framework were absent in these laws which was making their implementation difficult. The Constitution of India envisages a decentralized and participatory framework for natural resource management, and hence it was decided to modify 2005 groundwater policy by including these two principles. The draft of these modified bills has been made twice in 2011 and 2016.

15.1.2.1 Atal Bhujal Yojana (ABHY): National Groundwater Management Improvement (World Bank 2016)

Government of India with the help of World Bank expanded its Groundwater Management and Regulation (GWMR) Scheme which was started by Union government in 2013. Accordingly, the project with World Bank started from June 5, 2018, and it will continue up to September 29, 2023. Seven states Gujarat, Maharashtra, Haryana, Karnataka, Rajasthan, Uttar Pradesh and Madhya Pradesh have been selected to participate in the program. The program will include a provision that allows new states to be added over the implementation period.

ABHY primarily focuses on interventions to improve groundwater quantity. Interventions related to groundwater quality are restricted to planning and monitoring of groundwater quality as a needed first step given the limited knowledge on the dynamics of groundwater pollution pathways and potential actions to halt the deterioration of groundwater quality. The ABHY scope of activities can be classified into the following:

(i) Decision support tools for groundwater management.
(ii) State specific institutional framework for sustainable groundwater management.
(iii) Enhance groundwater recharge and improve water use efficiency.
(iv) Strengthen community-based institutions to foster management.

15.2 Statewise Extent of Contaminants in Groundwater

The main parameters that are considered to assess the contamination of groundwater by CGWB are salinity level; concentrations of fluoride, nitrate, arsenic and iron; and concentration of heavy metals like lead, chromium and cadmium. The concentration of all these elements is given in Table 15.1.

It is observed from the statewise statistics that the groundwater of the states like Punjab, Haryana, Uttar Pradesh, West Bengal, Tamil Nadu and Telangana was found to be contaminated by all studied elements. Iron was found to be major contaminant in most of the states. Out of 28 states, in about 75% of the states are having the problem of fluoride, nitrate and arsenic pollution, and 50% states are having the problem of salinity and lead contamination.

The statewise net annual groundwater availability and total annual groundwater draft of India (Fig. 15.1) depict that in the states like Haryana, Punjab and Rajasthan, groundwater has already been over-exploited with total annual groundwater drought more than the net annual groundwater availability.

Table 15.1 Statewise details of affected districts with groundwater contamination

SN	Name of the state	Salinity (EC >3000 micro mhos cm^{-1})	Fluoride (>1.5)	Nitrate (>45)	As (>0.01)	Fe (>1)	Heavy metals ($mg\ l^{-1}$)		
			< ---------------- ($mg\ l^{-1}$) ---------------------->				Pb (>0.01)	Cd (>0.003)	Cr (>0.05)
1.	Andhra Pradesh	11	11	13	3	7	–	–	–
2.	Arunachal Pradesh	–	–	–	–	4	–	–	–
3.	Assam	–	6	–	19	18	–	–	–
4.	Bihar	–	13	10	23	19	–	–	–
5.	Chhattisgarh	–	13	12	1	4	1	1	1
6.	Delhi	7	7	8	2	–	3	1	4
7.	Goa	–	–	–	–	–	–	–	–
8.	Gujarat	21	19	21	12	6	–	–	–
9.	Haryana	15	20	19	15	17	17	7	1
10.	Himachal Pradesh	–	–	6	1	–	–	–	–
11.	Jammu & Kashmir	–	2	4	3	6	3	1	–
12.	Jharkhand	–	12	11	1	6	1	–	–
13.	Karnataka	29	29	22	2	22	–	–	–
14.	Kerala	4	5	11	–	15	2	–	1
15.	Madhya Pradesh	16	39	50	8	42	16	–	–
16.	Maharashtra	20	17	30	–	20	19	–	–
17.	Manipur	–	–	–	2	1	–	–	–
18.	Meghalaya	–	–	–	–	3	–	–	–
19.	Nagaland	–	–	–	–	1	–	–	–
20.	Odisha	7	25	28	1	21	–	–	1

(continued)

Table 15.1 (continued)

SN	Name of the state	Salinity (EC >3000 micro mhos cm^{-1})	Fluoride (>1.5)	Nitrate (>45)	As (>0.01)	Fe (>1)	Heavy metals (mg l^{-1})		
			< ——————— (mg l^{-1}) ———————>				Pb (>0.01)	Cd (>0.003)	Cr (>0.05)
21.	Punjab	9	19	20	10	9	6	8	10
22.	Rajasthan	30	33	33	1	33	4	–	–
23.	Tamil Nadu	23	19	27	9	2	3	1	5
24.	Telangana	7	9	10	1	8	2	1	1
25.	Tripura	–	–	–	–	4	–	–	–
26.	Uttar Pradesh	9	30	46	29	15	10	2	4
27.	Uttarakhand	–	–	3	–	–	–	–	–
28.	West Bengal	4	7	2	9	15	6	2	2

Source: Ministry of Water Resources; Study on Groundwater contamination, March 30, 2018; PRS

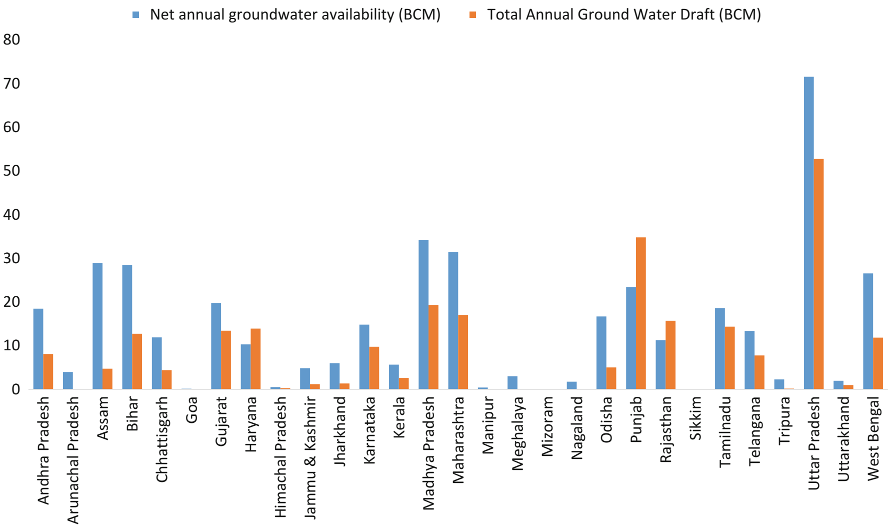

Fig. 15.1 Statewise net annual groundwater availability and total annual groundwater draft of India

15.3 Permissible Limits of Contaminants in Groundwater for Irrigation and Drinking Purposes as per Different Agencies

Keeping in view the fact that groundwater is used directly for drinking purposes by pumping through deep tube wells, its quality is of utmost importance and has been given importance in the National Water Policy. In India, agencies like the Bureau of Indian Standards (BIS) and Indian Council of Medical Research (ICMR) have guidelines for drinking water standards, while WHO depicts drinking water standards in the international arena. A comparison of drinking water standards for trace and toxic metals according to BIS, ICMR, CPHEO and USEPA are given in Table 15.2.

15.4 Groundwater Contamination by Urban and Industrial Wastewater

Rapid industrial growth in the so-called golden corridor area of Gujarat, especially Ankleshwar and Vapi, is presently transmitting a great stress to the environment. These industries generate huge volumes of wastewater laden with toxic heavy metals which pollute/contaminate the surface as well as groundwater resources, thereby posing a serious environmental concern through adverse effect on soil, aquatic life, plants, animals and human beings. Patel and Das (2015) reported the pH of

Table 15.2 Standards of different agencies for drinking water in India

Parameter	BIS	ICMR	WHO/FAO[a]	CPHEO	USEPA
Colour (Hazen unit)	5 (25)	2.5	15	2	15
Odour	Agreeable	Unobjectionable	Unobjectionable	Unobjectionable	–
Turbidity (NTU)	1 (10)	5	2.5 (5.0)	2.5	
pH	6.5–8.5	7.0–8.5	6.5–8.5	7.0–8.5	6.5–8.5
TDS (mg l^{-1})	500 (2000)	500	500 (1000)	500	
Total hardness (as $CaCO_3$) (mg l^{-1})	300 (600)	300	200 (500)	200	500
Ca (mg l^{-1})	75 (200)	75	75	75	
Mg (mg l^{-1})	30	50	30	30	
Cl (mg l^{-1})	250	200	200	200	250
SO_4 (mg l^{-1})	200 (400)	200	200 (400)	200	250
Fe (mg l^{-1})	0.3 (1.0)	0.1	0.1 (0.3)	0.1	0.3
Mn (mg l^{-1})	0.1 (0.3)	0.5	0.1	0.05	0.05
Cu (mg l^{-1})	0.05 (1.5)	0.05	0.2 (1.0)	0.05	1
NO_3 (mg l^{-1})	45 (100)	20	10 (45)	75	10
F (mg l^{-1})	1.0 (1.5)	1	1.5	1	2
Phenolic compounds (mg l^{-1})	0.001 (0.002)	0.001	0.001	0.001	
Hg (mg l^{-1})	0.001	0.001	0.001	0.001	0.002
Cd (mg l^{-1})	0.003	–	0.005	0.01	0.005
Co (mg l^{-1})	–	–	0.05–1.5	–	–
Ni (mg l^{-1})	0.02		0.02 (0.2[a])		
Se (mg l^{-1})	0.01	–	0.01	0.01	0.05
As (mg l^{-1})	0.01	–	0.01 (0.05)	0.05	0.01
Cn (mg l^{-1})	0.05	–	0.01 (0.1)	0.05	
Pb (mg l^{-1})	0.01	–	0.01 (0.05)	0.1	0.015
Zn (mg l^{-1})	5	–	–	5	5

Anionic detergents (mg/l)	0.2 (1.0)	–	–	0.2	
Cr (mg/l)	0.05	–	0.05 (0.1[a])	0.05	0.1
PAH (μg/l)	0.0001	–	–	0.2	
Mineral oil (mg l^{-1})	0.5 (0.03)	–	–	0.01	
Aluminium (mg l^{-1})	0.03 (0.2)	–	0.2	–	
Alkalinity ($CaCO_3$) (mg l^{-1})	200 (600)	–	–	–	
Boron (mg l^{-1})	0.5 (5.0)	–	–	–	
DO	5.0	5.0			
BOD	–	5.0			

BIS Bureau of Indian Standard (IS, 10500: 2012), Parenthesis values expressing permissible limit, *ICMR* Indian Council of Medical Research, *WHO* World Health Organization, *CPHEEO* Central Public Health and Environmental Engineering Organisation, *USEPA* United State Environmental Protection Agency

32 groundwater samples ranging from 6.31 to 8.06 (neutral to moderately alkaline) with mean values of 7.34 in the periphery of Vapi industrial belt (VIB). The Eklahare village situated at a distance of 700 m from VIB showed the higher salinity C3 class (1.95 dS m^{-1}) in water indicating to be unsafe for irrigation. The BOD and COD of these water sources varied from 62.2 to 84.0 mg l^{-1} and 136 to 304 mg l^{-1}, respectively; both values are higher than Indian Standards (IS). Higher BOD in water reflects poor aeration (inadequate oxygen) which adversely affects aquatic life and microbial activity in soil when used as source for irrigation (Patel and Das 2015), while presence of higher COD (69–193 mg l^{-1}) indicates ample quantity of contaminants/pollutants/organics in water sources (Yadav and Kumar 2011). In waterbodies near VIB, toxic contaminants like Pb and Ni were detected only in a few water sources. As Pb- and Ni-contaminated water might cause potential health hazards in human and aquatic ecosystem, this water cannot be used without suitable treatment for irrigation purposes; otherwise it contaminates the food chain through plant system.

Nandesari Industrial Estate (NIE) of Vadodara, Gujarat, situated on the bank of Mini and Mahi rivers constitute nearly 1200 small and big size dye, engineering, textile, pharmaceuticals and petrochemical industries which discharge sludge and sediments contaminated with toxic heavy metals in the Mini River (Patel and Parikh 2012; Mishra and Murthy 1995). The phosphate and lead loading were also higher in the NIE area, due to the contamination of river water with fertilizer runoff, detergent and domestic sewage and untreated discharge of industrial effluents in Mini River (Patel and Parikh 2012).

Due to rapid growth of industries in Maharashtra Industrial Development Corporation (MIDC), with nearly 600 small and big size industries of engineering, steel, processing, chemical, paints, pharmaceuticals, textile, etc., a huge discharge of untreated waste/effluents into the Kasardi River is happening. The average Ni of 10.8 mg l^{-1} and Pb of 33.9 mg l^{-1} content in water samples from nearby Taloja industrial belt of Mumbai were recorded which was higher than prescribed limit of drinking water (Lokhande et al. 2011) as per Indian Standards.

15.4.1 Indicators of Groundwater Contamination and Their Potential Health Hazards

(a) **pH:** It is a measure of the water reaction (acidity or alkalinity of water), measured at a scale of 0–14 at 25 °C. This parameter is common and very important for chemical reaction in the aquatic environment as it governs the direction and intensity of reactions. If water pH is either highly acidic or alkaline, accretion and toxicity of heavy metals may persist, which may show lethal effect to aquatic life.

(b) **Total Dissolved Solids (TDS)**: The TDS content in water is a measure of salinity and sodicity. In general, a wide range of salts exist in natural aquatic environment, especially carbonates, bicarbonates, chlorides, sulphates, phosphates and nitrates of calcium, magnesium, sodium, potassium, etc.

While excess of dissolved solids influence the density of water and affect osmoregulation in aquatic organisms, it also reduces solubility of gases and deteriorates its utility for drinking, irrigation and industrial purposes. The TDS values in the range of 6400 mg/l was recorded in downstream and 4586 mg/l in upstream of the Kasardi River (Lokhande et al. 2011), which are higher than prescribed limit (500 mg l^{-1}) for drinking purposes.

(c) **Biological Oxygen Demand (BOD)**: It can be defined as the removal of O_2 by microbes due to the degradation of the dissolved organic matter in water. BOD can be escalating with the discharge of industrial wastewater or effluents, animal/crop wastes and domestic sewage into waterbodies, which is a good indicator of pollution in water. BOD specifies the presence of decomposed organic matter in water derived from leaves and woody debris, dead plants and animals, animal manure, effluents from pulp and paper mills, wastewater treatment plants, feedlots and food-processing plants, failing septic system and urban storm water runoff. The BOD values in downstream of the river were recorded to be 214 mg l^{-1}, showing slightly higher pollution level (Lokhande et al. 2011).

(d) **Chemical Oxygen Demand (COD)**: Under acidic condition, most of carbon-based compounds with certain exemptions can be oxidized by the action of strong oxidizing agents. COD estimation is a measure of oxygen equivalent of that portion of the organic matter in a sample, which is vulnerable to oxidation reaction. Throughout the COD measurement, oxygen requirement rate is very convenient in stipulating toxic condition and presence of organically resistant/recalcitrant substances. It is a very important, rapidly measured parameter of organic contamination in industrial wastewater. Both COD and BOD are the measure of the relative oxygen-depletion effect of a wastewater contaminant. In the Mumbai industrial belt, COD values ranged between 68 mg l^{-1} and 690 mg l^{-1} in upstream and downstream, respectively, of the Kasardi River (Lokhande et al. 2011), which are higher than maximum permissible limit. The effect of contaminated groundwater in developing adverse conditions in plants, aquatic life and human being has been elucidated (Table 15.3).

15.4.2 Groundwater Contamination by Industrial Effluents

During the past decades, groundwater quality is deteriorated in alarming rate especially northern states of India due to increasing industrialization, urbanization and agricultural activities (CGWB 2005). Groundwater contamination as a result of water pollution in the waterbodies can frequently show severe unpleasant ill effect on all kind of living organisms. Water pollution is a major challenge at global level and occurs when contaminants are discharged directly or indirectly without any treatment of industrial waste effluents for removing toxic or hazardous constituents (Matta 2015). In the rural areas for irrigation as well as drinking purposes, people are

Table 15.3 Health hazards in plants, aquatic life and humans due to poor groundwater condition

Indicators of water quality	Toxic symptoms/effect		
	Plants	Aquatic life	Human/terrestrial life
pH		Highly acidic or alkaline environment kill marine life	
Oil and grease content	Affect the transmission of light, reduced photosynthesis	Insulating properties of animals' feathers, detergents create frothing and harm in vertebrates and fishes	
COD/ BOD		Crisis of oxygen in water for higher aquatic life, aquatic organism become stress, suffocate, die Bad smell of water	
TDS		Density of water influences osmoregulation of freshwater in organisms	Reduces solubility of gases (like oxygen) and utility of water for drinking, irrigation and industrial purposes
Cr	Inhibition of seed germination and seedling growth, reduction of root growth, leaf chlorosis and depressed biomass	Acute toxicity invertebrates is highly variable	Generally, more toxic at higher temperature; skin irritation (ulceration), kidney, liver, circulatory and nerve tissue damage, cancer in human
Cd	Similar toxic to Cr	Equally toxic to invertebrates and fishes	Few ever instances of Cd poisoning
Ni		Accretion in aquatic life	In human, long-term exposure can cause decrease in body weight, heart, liver damage and skin irritation
Zn	Necrosis, chlorosis and inhibited growth of plants		
Cu	Damage to roots, by attacking the cell membrane and destroying the normal membrane structure; inhibited root growth and formation of numerous short, brownish secondary roots	Highly toxic to most fishes, invertebrates and aquatic plants than any other heavy metal	Reduces growth and rate of reproduction in animals
Pb	Severe growth retardation, discoloration and morphological abnormalities. Adverse	Acute toxicity of Pb in invertebrates (0.1–10 mg l^{-1}) Higher levels	

(continued)

Table 15.3 (continued)

Indicators of water quality	Toxic symptoms/effect		
	Plants	Aquatic life	Human/terrestrial life
	effect on photosynthesis, respiration and other metabolic processes	pose eventual threat to fisheries resources	

mainly dependent on groundwater source. Due to increase in urbanisation, waste production and discharge are increasing gradually (Bhadauriya et al. 2011; Arora et al. 2014).

Textile industries require ample amount of water, as a result producing a massive volume of wastewater, which are discharged into a common effluent drain of industrial area. It contains high concentration of heavy metals, organic contaminants and toxic colours, which may adversely affect the quality of surface water, soil, groundwater, plant kingdom as well as living entities. Toxic contaminants percolate or leaching throughout the soil profile and deposited in groundwater (Kumar et al. 2001), which ultimately cause the health hazards among human being as well as livestock consumption through intake of water for living (Bharti 2007; Malik and Bharti 2010). Therefore, it is crucial to measure the contaminants from the industrial vicinity areas for its behaviour, where wastewater has been discharged in common industrial drain, which uses it as irrigation purposes.

Average concentration of heavy metal, i.e. Cd, Ni and Pb, was 1.927, 7.96 and 42.358 mg kg^{-1}, respectively, in surface soils irrigated with contaminated groundwater from textile industrial area of Panipat (Haryana) (Bharti et al. 2013). It was found that the higher concentration of Pb was attributed to its cumulative and adsorptive nature in soil after repeated irrigation by contaminated groundwater, while Cd were found minimum due to their weak adsorptive nature in soil. Bharti et al. (2013) reported that the maximum transfer factor (TF) values were obtained for Cd (321.11) and Ni (83.49) from groundwater to agricultural soil, which showed one key mechanism of human exposure to metals through food chain (Lokeshwari and Chandrappa 2006), while from soil to groundwater, the TF for metals is comparatively less (Table 15.4). This finding showed that persistence of Pb is more in groundwater and soil systems, which specified the transfer of heavy metals from groundwater to agricultural soil system due to the repeated irrigation practices. The bioavailability and mobility of metals added via effluent irrigation govern their uptake by plants and potential food chain contamination (Yadav et al. 2003; Sharma et al. 2007). Organic pollutants are biodegradable, but metals are non-biodegradable and accumulate in soils with initially fast retention and subsequently slow reaction and ultimate quasi-ready state between available and residual form (Han et al. 2003; Lokeshwari and Chandrappa 2006).

In the industrial zones of Gujarat, the Ankleshwar Industrial Estate (AIE) is one of the biggest industrial hubs of India, which comprises Ankleshwar and Panoli industrial areas. Both areas have more than 3000 industrial units including small and

Table 15.4 Heavy metals in effluent, groundwater and soils and transfer factor between from effluent to groundwater, from groundwater to irrigated agricultural soil and from soil system to groundwater

Metals	Effluent ($mg\ l^{-1}$)	Groundwater ($mg\ l^{-1}$)	Soil ($\mu g\ g^{-1}$)	Effluent vs groundwater	Groundwater vs agricultural soil	Agricultural soil vs groundwater
Cd	0.014	0.006	1.927	0.436	321.111	0.003
Ni	0.034	0.095	7.960	2.790	83.497	0.012
Pb	0.404	1.284	42.358	3.178	32.980	0.030

Source: Bharti et al. (2013)

big sizes, half of which are chemicals, manufacturing dyes, paints, fertilizers, pharmaceuticals, industrial chemicals, pulp and paper and pesticides (Bruno 1995, CPCB 1996). These units are producing 250–270 million litre/day of liquid waste (Bruno 1995), which is discharging into common industrial drains (Amla Khadi) covering nearby the Ankleshwar and Panoli areas. The analysis of pre- and post-monsoon data revealed the high degree of spatial and temporal variability. Among heavy metals, average Ni, Mn and Cu concentration is increased by 24, 10 and 12 times after monsoon, respectively, while in case of Zn, the concentration was decreased, whereas in Pb case concentration was unchanged (Kumar and Pawar 2008).

In one of the studies conducted by ICAR Central Soil Salinity Research Institute, Regional Research Station, Bharuch, groundwater samples were collected from 50 sites along Amla Khadi and Wandi Khadi, tributaries of Narmada, as well as from locations close to the industrial estates of Ankleshwar and Panoli in Gujarat, India, during two different seasons, viz. pre-monsoon (PRM) and post-monsoon (POM) in the months of May 2016 and December 2016, respectively. The sampling sites were specifically chosen in order to assess the impact of effluents on groundwater quality. The heavy metal pollution index (HPI) is a commonly used technique to measure the overall quality of water based on the cumulative presence of individual heavy metal. The HPI model (Mohan et al. 1996) based on weighted arithmetic mean of heavy metal concentrations was used in this study. In this model, the unit weightage is inversely proportional to the recommended standards of the corresponding parameter, and the model is represented as

$$\mathrm{HPI} = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i=1}^{n} W_i}$$

where Q_i is the subindex of the ith parameter, W_i is the unit weightage of the ith parameter and n is the number of parameters considered.

For calculation of the subindex (Q_i) of the parameter, the following formula is given:

$$Q_i = \sum\nolimits_{i=1}^{n} \frac{|M_i - I_i|}{S_i - I_i} \times 100$$

where M_i is the monitored value of heavy metal of ith parameter, I_i is the ideal value of ith parameter and S_i is the standard value of ith parameter. The numerical difference of the two values (M_i and I_i) has been taken as absolute value irrespective of the algebraic sign. The concentration limits given by Bureau of Indian Standards (BIS 2012) were taken for this study, and the critical pollution index of HPI value for drinking water is 100 as proposed by Prasad and Bose (2001). Significant findings have emerged from this study of heavy metal contamination in groundwater. Cadmium was found to be above the acceptable levels for drinking water in both the PRM and POM seasons and showed less seasonal variability. Cu, Cr, Mn and Ni were found to be above the acceptable levels in the PRM season whereas these heavy metals were within the acceptable level in the POM season and showed considerable seasonal variability. HPI values indicated that 82% of the samples in the PRM season and 68% in the POM season were of poor-quality water and unfit for drinking.

15.4.3 Urban Sewage Waste

Unavailability of good-quality irrigation water, scanty and erratic rainfall patterns has compelled most of farmers to use contaminated commercial and industrial effluent without any treatment. In the Mamurabad watershed area near the Jalgaon urban centre (Maharashtra), Yeole et al. (2012) assessed the pollution levels in black cotton soil and water quality for irrigation purposes. Under four sewage water streams leachates, average pH, hardness, total solids, TDS, chloride, sulphate, BOD and COD ranged from 7.79 to 7.93, 1010 to 1166.6 mg l^{-1}, 1706.6% to 4960%, 726.6% to 3073.3%, 220.56 to 333.2 mg l^{-1}, 77.33 to 142.3 mg l^{-1}, 253.3 to 388 mg l^{-1} and 823.3 to 983.3 mg l^{-1}, respectively, indicating its potential to affect the surface water as well as groundwater and soil quality. The heavy metal concentrations (0.99 mg kg^{-1} Pb, 0.25 mg kg^{-1} Ni and 0.034 mg kg^{-1} Cd) were also recorded in the agricultural soils of adjoining areas of Lendhi Nala due to discharge of domestic waste (Yeole et al. 2012). The harshness of pollution in soil and water quality in this area is currently medium, but in the near future, it may pose serious threats.

15.5 Major Groundwater Contaminants in India

15.5.1 Arsenic

Arsenic (As) is an odourless and tasteless metalloid distributed widely in the earth's surface and subsurface. Arsenic and its compounds occur in crystalline and amorphous forms. It generally persists in trace amounts in different rocks, soil and water. Arsenite [As(III)] is most toxic form of arsenic and causes acute toxicity in humans and animals. The contamination of arsenic in groundwater has received large attention in recent times. The problem of arsenic contamination of groundwater was first recorded in 1978 in West Bengal, and since then studies revealed the occurrence of natural arsenic in groundwater in central and eastern Indian Ganges plains, the state of Chhattisgarh, the north-eastern states and several other regions of India (Table 15.5) with about 50 million people at the risk of its adverse effects. Arsenic contamination may also result from anthropogenic sources, mainly mining of sulphide ores and smelting activities, coal mining and related processes; effluent sewage discharge, arsenic-containing pesticides, and wood preservatives have caused arsenic problems in the Indian soils. When As-contaminated groundwater is extensively used for irrigation, arsenic enrichment in the soils and the crops is a common phenomenon.

Table 15.5 Arsenic in different aquatic environments in India

Surface water	Water ($\mu g\ l^{-1}$)	Sediment ($mg\ kg^{-1}$)
Lake Chilika, Orissa	35	–
Alaknanda River, Devprayag	6.3	–
Bhagirathi River, Devprayag	4.6	–
Ganges, Bhagalpur	4.2	–
Bhagirathi-Hooghly (West Bengal)	0.3–4	–
Jalangi River	55–101	–
Ichamati River	37	–
Baitarani River	0.1–2.1	–
Mahanadi River	0.1–3	–
Ganges River	–	2–9
Brahmaputra River	–	2–6
Yamuna	–	3–11
Narmada and Tapti rivers	–	3–5
Godavari River	–	4–14
Krishna River	–	2–5
Cauveri River	–	2–4
Shivnath River	100–300	
Groundwater	–	–
Western Bengal basin, West Bengal	<1–4200	
Middle/Lower Ganges plain, Bihar	<10–1654	–
Middle/Lower Ganges plain, Jharkhand	<1–620	–
Central Indian igneous terrain, Chhattisgarh	<1–700	–
Upper Ganges plain, Uttar Pradesh	<1–880	–
Brahmaputra basin, Assam	<1–657	–
Mineralized areas, Rajasthan	<1–13.8	–

Source: Konhauser et al. (1997), Mandal et al. (1996), Madhavan and Subramanian (2000), Subramanian et al. (1985), Chakrapani (2005), Mukherjee et al. (2007), Mukherjee and Fryar (2008) and Pandey et al. (2002)

15.5.1.1 Sources of Arsenic in India

(a) Natural Sources

Leaching of arsenic in groundwater due to dissolution of sediments containing arsenic-bearing minerals contaminates groundwater. Presence of arsenic in the Ganges plains and delta sediments seems to be of pedogenic/geogenic origin (originated from the Himalayan Mountains and the Shillong Plateau). Besides, some other sources are:

(a) Gondwana coal deposits in the Rajmahal basin, eastern India (arsenic: 0.02%).
(b) Bihar mica belt in eastern India (arsenic concentration ranges from 0.08% to 0.12%).
(c) Pyrite-bearing shale from the Proterozoic Vindhyan range, central India (0.26% arsenic).

(d) Son river valley, eastern India, containing arsenic with average concentration of 2.8%.
(e) Isolated outcrops of sulphides in the eastern Himalayas containing 0.8% arsenic.

(b) **Anthropogenic Sources**

Arsenic is an integral constituent of several agrochemicals, wood preservatives, mineral processing industries, acid mine drainage, fossil fuels burning, etc. As is released to the environment through several pyrometallurgical, nonferrous metal mining and production, iron and steel manufacturing and coal combustion which deal with very high temperature release of arsenic to the environment. The degree of arsenic release from these processes depends on several factors:

1. Ore mineralogy.
2. Physiochemical properties of an ore.
3. Technology linked to the production system and the efficiency of the gas cleansing equipment.

15.5.1.2 Mode of Entry of Arsenic in the Human Body.

Arsenic can enter the human body through drinking water as well as contaminated food. Since it occurs naturally in the environment and also is a by-product of some agricultural and industrial activities, it can contaminate drinking water through the groundwater or as runoff into surface water sources. When crops are irrigated with arsenic contaminated groundwater, inorganic forms of arsenic (arsenite) get translocated in the plant system and hence contaminate the food cycle. The maximum permissible limit of arsenic in drinking water is 10 ppb (WHO) in most of the developed countries. In developing countries including India and Bangladesh, the accepted level is 50 ppb.

15.5.1.3 Major Arsenic-Contaminated Regions in India

The reports of arsenic contamination in groundwater of India are widely published. Majority of these studies have been conducted in the Lower Ganges plain and delta of the eastern West Bengal due to the severity of health-related issues. Besides West Bengal, arsenic contamination has also been reported in the Ganges plains of Bihar, Uttar Pradesh, and Jharkhand; the Brahmaputra valley of Assam and some pockets of Punjab, Haryana and Himachal Pradesh; adjoining areas of New Delhi; and the state of Rajasthan.

Significantly high concentrations of As are reported in the mining areas of Rajasthan, in Western India especially around the mining areas of Khetri Copper Complex and Zawar mines in Jhunjhunu and Udaipur districts, respectively. In Bihar, mines of sulphide-bearing copper and lead ores have arsenic as impurity, which, if mobilized, may significantly contaminate the groundwater resources. Coal mines are also a potential source of arsenic contamination as the average concentration of arsenic in Indian coal ranges up to 0.15–0.40 mg/kg. Fertilizers and various pesticides, insecticides, herbicides and fungicides often contain significant amount of arsenic which may lead to considerable groundwater contamination especially in Punjab, Andhra Pradesh, Haryana, Karnataka, Tamil Nadu, West Bengal and Uttar Pradesh (UP).

15.5.1.4 Mechanisms of Arsenic Mobilization in Groundwater

The mechanism of arsenic mobilization in groundwater can be explained by the following processes.

(a) **Oxidation of pyrite**

The oxidation of arsenic-bearing pyrite within the alluvial sediments release As in the system. Such oxidation is favoured by excessive pumping of groundwater and consequent drop of water table leading to aeration of previously anoxic sediments.

(b) **Competitive ion exchange**

It is reported that arsenic oxyanions adsorbed to aquifer sediments (mostly to Fe oxyhydroxides) are replaced into solution phase by competitive exchange with PO_4^{3-} introduced through the addition of phosphatic fertilizers.

(c) **Reductive dissolution of Fe oxyhydroxides**

The reductive dissolution of arsenic sorbed onto the Fe oxyhydroxides in natural sediments is a major process of As contamination.

(d) **Reduction and reoxidation**

In this phenomenon, mobilization of Arsenic occurs via reduction of Fe oxyhydroxides and subsequent reoxidation of pyrite due to O_2 influx. Later, oxidized Fe and S may be reduced, thus resequestering arsenic, suggested through isotopic studies. However, it has been reported that liberated arsenic is partially immobilized under strongly reduced conditions and thus is retained in the solution phase as a result of partial redox equilibrium. The fluctuations of water table between dry and wet seasons result in alternate oxidation of sulphides and reduction of Fe oxyhydroxides in surface soils which cause the movement of residual As and S into the shallow aquifer.

15.5.2 Nitrate Pollution in Groundwater

Contamination of nitrate in groundwater is mainly through the addition of different nitrogen sources either on the land surface (fertilizer application in agriculture) or subsurface (burial of nitrogen-rich organic matter). Nitrogenous fertilizers application in agricultural fields is also the potential source of nitrate pollution in groundwater. The N fertilizers are applied mostly in amide (urea), ammonium (ammonium sulphate, ammonium chloride, etc.) and nitrate form ($NaNO_3$). These forms undergo ammonification and nitrification and get converted to nitrate. Nitrate being an anion gets repealed by the soil clay fractions and thus leaches down the soil profile and contaminates the groundwater.

In a study, 2500 groundwater samples (2000 from dug wells and 500 from deep tube wells) throughout India were analysed (Handa 1975). It was hypothesized that higher nitrate concentrations in the samples were due to decomposition of organic sources of animal and human origin as well as runoff from agricultural fields, dressed with fertilizers. It was observed that nitrate concentration varied with depth of water table and rainfall (1–2 mg l^{-1} in shallow depth and up to 100 mg l^{-1} in deep groundwater in humid areas and 1000 mg l^{-1} in arid and semiarid regions). Another study in 1978 from UP with 276 groundwater samples recorded that a number of wells with nitrate concentration below 10, 20, 50 and 100 mg/l were 53.6%, 71.7%, 89.5% and 95.3%, respectively (Pathak 1980). High concentration of nitrate, ranging from 2.8 to 91 mg l^{-1}, was recorded in water samples collected from hand pumps in the industrial belt of Ludhiana town (Goyal et al. 1981). Kakar (1981) observed significantly high concentrations of nitrate of 1800 and 1620 mg l^{-1}, respectively, in Hisar and Mahendragarh districts of Haryana. Gupta (1981) and Gopal et al. (1983) studied the groundwater nitrate concentration in Barmer and Jaipur recorded >11.3 mg l^{-1} NO_3-N in 74% and 40% of groundwater samples, respectively. Lakshmanam et al. (1986) collected groundwater samples from 75 dug wells and 35 tube wells from Hyderabad and Secunderabad and found the mean nitrate contents in dug and tube well waters were 118.7 mg l^{-1} and 63.3 mg l^{-1}, respectively. Tamta (1996) showed 18% of groundwater samples collected from an area of 1475 km^2 in Bangalore district (Karnataka) had average nitrate concentration more than 50 mg/l with a maximum of 200 mg/l. Groundwater Pollution Directorate (1993) of Central Ground Water Pollution at Lucknow has reported groundwater nitrate in Varanasi City area (Table 15.2). High concentration of nitrate (65–550 mg l^{-1}) was found in groundwater of the human and animal settlements of some areas in Karnataka (Tamta 1996). The nitrate concentrations in the groundwater samples of different locations in Varanasi, Delhi and Punjab are depicted in Tables 15.6, 15.7 and 15.8, respectively.

15.5.3 Fluoride

Presence of fluoride in drinking water above the permissible limit is detrimental to human and animal health (USPHS 1987; WHO 1984; Handa 1975). Fluoride in groundwater is of geogenic origin; however the process of dissolution is still a mystery (Handa 1975; Saxena and Ahmed 2001). The source of its contamination is mainly a non-point source. In a study, 58 fluoride-rich groundwater samples were collected from different parts of India indicating that fluoride concentration was from 1.7 to 6.1 mg l^{-1}. It is hypothesized that presence of fluoride-bearing minerals in the host rocks and its subsequent decomposition, dissociation and dissolution cause fluoride contamination in groundwater. The location, pH, geochemical and geological information of the water samples and the fluoride concentrations of the different fluoride-rich areas of India are depicted in Table 15.9.

Table 15.6 Nitrate content in groundwater of Varanasi

Sector of city area	Location	Groundwater structure		NO_3 level (mg l^{-1})
		Type	Depth (m)	
Northern	Shivpur	DW	10.35	284
	Paigambarpur	DW	17	62
	Ashapur	DW	19.20	59
	Chiraigaon	DW	15.30	59
	Kamauli	HP	40	342
		DW	20	99
Central	Alaipura	DW	13.90	66
	Bhojpur	DW	16.80	199
	Shivdaspur	DW	16.70	128
	Lohta	DW	15.60	180
Southern	Kakarmatha	DW	20.50	100

15.5.4 Nickel

It is a transition element (atomic no. 25 and atomic wt. 58.69), which occurs in the environment only at very low levels and essential in small doses, but it can be hazardous when it crosses the permissible limits. It is also discharged in common wastewater industrial drains through producing wastewater industries and mixed with surface water. The most portions of all Ni compounds which are released to environment will occupy to sediments or soil particles and convert as a result in fixed/immobile form while, Ni in acidic condition, transform to more mobile and frequently percolate down to the groundwater.

Ni	At low pH condition →	Ni(II)
Ni	Neutral to slightly alkaline condition →	$Ni(OH)_2$ precipitated as nickel (II) hydroxide (stable compound)
$Ni(OH)_2$ (precipitate)	Readily dissolve in acid solution →	Ni(III)
$Ni(OH)_2$ (precipitate)	Very alkaline condition →	$HNiO_2$ (nickelite ion), i.e. soluble in water
Ni	Very oxidizing and alkaline conditions →	Ni_3O_4 (stable nickel-nickelic oxide); soluble in acid solution
Ni	Other oxides of Ni →	Ni_2O_3 (nickelic oxide) and NiO_2 (nickel peroxide); unstable in alkaline condition
Ni_2O_3 and NiO_2	Acidic regions; $-O_2$ →	Ni^{2+} (Pourbaix 1974)

Table 15.7 Groundwater nitrate content in some areas of Delhi

Areas	NO_3 (mg l^{-1})	Areas	NO_3 (mg l^{-1})
Block-Kanjhawala		Bokali	113
Kanjhawala	140	Mamurpur	236
Mohammad Pur Mairi	161	*Block-City*	
Mundka	119	India Gate Nursery	121
Kirari	184	Delhi Zoo	1589
Sultanpuri	208	Jamia Millia Market	194
Mangol Pur Khurd	114	Vasant Enclave	133
Mangol Pur Kalan	652	Hastsal	171
Nijampur	106	Parsi Dharmashala	100
Mangolpuri	180	Naharpur	108
Bhagey Bihar	115	Jeevan Nagar	232
Jat khor	390	Kishanganj	190
Krishna Bihar	184	Kotla Mubarakpur	328
Block-Najafgarh		Sanjay Camp	240
Palam Gaon	105	Sudarshan Puri	202
Chhawla	130	Shanti Van	144
Kangan Hari	300	Okhla Ind. Phase I	110
Kharkhari Nahar	203	Sarita Vihar	149
Kakrola	379	New Friends Colony	102
Pindwala Kalan	361	Naraina	600
Dhansa	377	Begampur	240
Ujwa	508	*Block-Shahdara*	139
Jharoda Kalan	208	Ghazipur	180
Dichaon	178	East Vinod Vihar	141
Neejwal	117	Durga Puri Chowk	
Gazipur	389	*Block-Mehrauli*	
Kair	264	Dera Gaon	690
Isapur	106	Rajokari Road	262
Block-Alipur		Gadaipur	743
Puth Khurd village	266	Jaunapur	124
Palla	277		

Table 15.8 Groundwater nitrate content in different areas of Punjab

Block	No. of wells	Range	Fertilizer N consumption (kg ha^{-1} $year^{-1}$)
Dehlon	84	1.14–6.72	249
Ludhiana	33	0.50–5.90	258
Sudhar	43	1.20–6.48	242
Kartarpur	34	1.14–6.72	193
Jandiala Guru	84	1.14–6.72	172
Malerkotla	18	1.40–5.80	151

Table 15.9 Location, depths and main geochemical and geological information of the water sampling stations from fluoride-rich areas of India

Sample No.	Sample location	Sp. Cond. (µS cm^{-1})	pH	Ca (mg l^{-1})	HCO_3 (mg l^{-1})	F (mg l^{-1})	Well depth (m)	Geological formation
Rajasthan								
1	Sankholi	1960	8.6	58	376	2.5	36.5	Tertiary, Mesozoic and Upper Paleozoic sediments
2	Jaisalmer	2020	7.85	76	439	4.7	45.5	Tertiary, Mesozoic and Upper Paleozoic sediments
3	Gangasagar	680	8.2	28	70	2.1	25.8	Quaternary-Upper Tertiary deposits
4	Nagaur	1200	7.9	32	110	2.6	17.3	Quaternary-Upper Tertiary deposits
5	Barmer	2200	8.1	69	357	4.3	33.1	Tertiary, Mesozoic and Upper Paleozoic sediments
6	Bikaner	2150	8.2	25	485	2.8	28.2	Quaternary-Upper Tertiary deposits
7	Jayal	2470	7.9	102	402	3.2	27.2	Quaternary-Upper Tertiary deposits
Uttar Pradesh								
8	Unnao	735	8.3	8.3	108	2	3.1	Quaternary-Upper Tertiary deposits
9	Debraspur	1050	7.7	7.7	105	2.1	7.5	Quaternary-Upper Tertiary deposits
10	Janghai	1510	8.1	8.1	255	3.2	3.6	Quaternary-Upper Tertiary deposits
11	Kulpahar	1615	8.1	8.1	305	3	2.8	Quaternary-Upper Tertiary deposits
12	Babera	1605	8.2	8.2	325	3.3	7.6	Quaternary-Upper Tertiary deposits
13	Karchhana	910	8.4	8.4	98	2.8	7.2	Quaternary-Upper Tertiary deposits
14	Jhansi	935	8.6	8.6	152	2.8	3.8	Quaternary-Upper Tertiary deposits
15	Etah	1180	8.0	8.0	210	3	3.2	Quaternary-Upper Tertiary deposits
Haryana								
16	Didwana	1368	7.4	69	210	2.2	6.5	Quaternary-Upper Tertiary deposits
17	Mahendragarh	1410	7.9	53	242	2.3	6.3	Quaternary-Upper Tertiary deposits
18	Bhiwani	2601	8	86	365	4.2	5.2	Quaternary-Upper Tertiary deposits
19	Hisar	2396	7.6	76	486	6.1	24.2	Quaternary-Upper Tertiary deposits

(continued)

Table 15.9 (continued)

Sample No.	Sample location	Sp. Cond. (μS cm^{-1})	pH	Ca (mg l^{-1})	HCO_3 (mg l^{-1})	F (mg l^{-1})	Well depth (m)	Geological formation
20	Gurgaon	2379	7.8	102	336	1.8	23.8	Quaternary-Upper Tertiary deposits
21	Sirsa	2155	8.2	58	356	2.8	4.2	Quaternary-Upper Tertiary deposits
22	Kuksi	875	8	30	105	2.1	4.1	Quaternary-Upper Tertiary deposits
Karnataka								
23	Palar	530	8.4	22	75	2	3.6	Archaean granite and gneissic complex
24	Hanagal	580	8.5	20	88	2.2	5.6	Archaean granite and gneissic complex
25	Bhominpalya	610	8.5	15	75	2.2	4.2	Archaean granite and gneissic complex
26	Wadgora	1800	8.2	62	175	3.1	3.8	Archaean granite and gneissic complex
27	Kadechur	1160	8.4	40	205	3.2	3.7	Archaean granite and gneissic complex
28.	Sindhanur	1005	8.1	35	120	2	4.6	Archaean granite and gneissic complex
29.	Bellary	1235	8.2	45	185	2.2	3.3	Archaean granite and gneissic complex
Andhra Pradesh								
30	Palavi	1100	8.5	38	205	1.9	3.3	Archaean granite and gneissic complex
31	Nandigama	1540	7.8	106	350	5.5	3.2	Archaean granite and gneissic complex
32	Gopalapuram	875	7.8	41	130	1.8	7.5	Archaean granite and gneissic complex
33	Nalgonda	1450	8.1	68	405	3.2	8.1	Archaean granite and gneissic complex
34	Hindupur	1630	8	48	270	4.5	8.2	Archaean granite and gneissic complex
35	Warangal	1255	7.8	52	242	3.2	3.4	Archaean granite and gneissic complex
36	Prakasham	1050	8.4	42	115	2.8	3.2	Archaean granite and gneissic complex
37	Kothagudem	1710	8.3	58	305	3.0	7.5	Archaean granite and gneissic complex
Maharashtra								
38	Chandrapur	1600	8.8	98	302	3.5	5.0	Basalt
39	Pijdura	1100	7.7	51	188	2	5.1	Basalt
40	Sakara	2680	7.7	75	445	1.8	3.8	Basalt
41	Gadegaon	1470	8.4	52	275	2.3	8.5	Basalt

42	Bhoyar	2000	7.8	66	402	2	8.2	Basalt
43	Pandhurna	1550	7.7	50	352	2.2	9.1	Basalt
44	Gandhigram	875	8.1	30	110	1.8	9.5	Basalt
45	Sagargaon	850	7.7	38	185	2.7	3.8	Basalt
46	Singpur	1652	8.1	76	315	4.3	4.2	Basalt
47	Karlakot	1050	7.5	42	205	2.4	4.6	Basalt
48	Durkapada	616	7.7	22	100	1.7	23.5	Basalt
49	Nayagartpuri	1120	8.1	58	255	2.1	20.8	Basalt
50	Kednapara	1680	8.3	72	328	3.7	4.0	Basalt
Bihar								
51	Champaran	1230	8.4	48	240	3.1	3.2	Quaternary-Upper Tertiary deposits
52	Madhubani	1100	7.6	32	185	3.2	3.9	Quaternary-Upper Tertiary deposits
53	Kajra Munger	610	7.4	20	55	2.5	2.8	Quaternary-Upper Tertiary deposits
54	Bhagwanpur	1425	8	56	275	2	3.0	Granite and gneisses
55	Pipra/Saharsa	830	8.1	44	110	3	3.1	Granite and gneisses
Madhya Pradesh								
56	Jabalpur	1130	7.5	45	130	2.2	20.2	Tertiary, Mesozoic, Upper Paleozoic sediments
57	Devgaon	1080	8.1	36	104	3.4	4.1	Tertiary, Mesozoic, Upper Paleozoic sediments
58	Begumganj	855	7.8	20	75	3.2	3.8	Tertiary, Mesozoic, Upper Paleozoic sediments

15.5.5 Selenium

Se is a metalloid, intermediate in properties between the metals and non-metals, which existed throughout the world, but only small quantities. The existence of Se in soils is very heterogeneous, varied from 0.1 to 2.0 mg/kg depending on terrestrial environmental area (Dhillon and Dhillon 2003; Moreno-Rodriguez et al. 2005) and vary from deficient to toxic levels (Hartikainen 2005). Soils comprising more than 0.5 mg/kg are reflected as toxic, which are directly goes to animal food chain through consumption of Se-laden vegetation (Dhillon et al. 1992). Soils from different states of northwestern India showed wide variation in Se content. Total and water-soluble Se content of surface soils in Gujarat state varied from 0.14 to 0.68 and 0.05 to 0.12 mg kg^{-1}, respectively (Patel and Mehta 1970). In seleniferous and adjoining non-seleniferous areas in Punjab, Se content of soils ranged from 0.31 to 4.55 and 0.08 to 0.55 mg kg^{-1}, respectively. Water-soluble Se constituted 2–18 per cent of total Se in these soils (Dhillon et al. 1992). Selenium content of tube well waters at or near the toxic sites varied from 0.25 to 69.5 μg l^{-1} (Dhillon and Dhillon 2003). These values exceeded the maximum permissible level of 10 μg l^{-1} for drinking purposes and 20 μg l^{-1} for irrigation purposes. Selenium pollution occurred from both natural (weathering of rocks especially Se-laden shales) and anthropogenic sources (Minorsky 2003), as a weathering of shales by water dissolution through excessive irrigation, which accelerate weathering process. Apart from this, mining also speeds up the potential risk of Se toxicity by direct contact of rocks to air, which enforces towards the solubilization of Se, which enters soils through deposition from coal combustion and firing of municipal wastes. Se is also accredited in soils by using fertilizers especially ammonium sulphate and SSP (White et al. 2004). So, weathering of Se-laden rocks, water and wind erosion and deposition process spread the Se particles on top surface layer of soil. Se bioavailability, however, is determined by many factors including soil pH, the redox potential, soil texture, organic matter contents and presence of competitive ions, artificial fertilization and the rate of rainfall.

Selenate is more soluble and available for plants under oxidized and alkaline soil conditions (Mayland 1994). Selenite is less available to plants as it is adsorbed more strongly by iron oxide surfaces and soil clays (Mikkelsen et al. 1989). In acidic poorly aerated soils, Se occurs mainly as insoluble selenides and elemental Se. It generally occurs uncombined, normally in adjunction with free sulphur, which generally occurs together with the sulphides as selenides in ores of such metals as Fe, Pb, Ag and Cu. It occurs as compounds Se, which existed in −2, +2, +4 and + 6 oxidation states. While the elements itself are not hazardous or poisonous, most of its compounds are extremely toxic. It combines directly with hydrogen, as product in hydrogen selenide (H_2Se), which is colourless, foul-smelling gas, i.e. poisonous. Selenium also forms selenides with many metals such as aluminium selenite, cadmium selenide and sodium selenide, while selenite complexes with common components such as ferric and aluminium sesquioxides, although selenite does not form such type’s complexes and is easily percolate or leached from soil to groundwater.

Elemental Se	$\xrightarrow{\text{Acidic and reducing condition}}$	Inorganic selenites (water soluble)
Elemental Se	$\xrightarrow{\text{Alkaline and oxidising condition}}$	Selenates (water soluble) – leached down

Selenites and selenates both are water soluble, which both form percolate through gravity on well-drained alkaline condition, while elemental selenium and selenides are water-insoluble forms. Insoluble forms having tendency to be adhere in moist and waterlogged conditions. So, under alkaline condition, selenium bioavailability is favourable for plant uptake, while under low pH condition, selenium availability is limited due to fixation of selenites and selenates forms with Fe and Al_2O_3 in soils. The heavy metals contamination in groundwater samples of different places in Tamil Nadu, Odisha, Assam, Pondicherry and Rajasthan are showed in Table 15.10.

15.5.6 Pesticide Contamination in Groundwater of Different Regions of India

The increased use of plant protection chemicals (herbicides, insecticide, fungicide) for increasing agricultural productivity has led to the contamination of groundwater through leaching of the toxic compounds. Some of the important pesticides found in the groundwater of North India (Delhi and Haryana), Western India (Maharashtra) and South India (Kerala) along with their concentrations are given in Table 15.11.

15.6 Remediation of Groundwater Pollution

The importance of groundwater as a natural resource cannot be overlooked. An overwhelming majority of the people in India depend on groundwater for drinking (85%) and irrigation (60%) purposes. When groundwater gets contaminated, it proves to be very perilous. It is very important to find and explore cost-effective ways to free groundwater from contaminants so that it can be used by the present and future generations. There are different ways to remediate the groundwater contaminated with different kinds of pollution which is discussed below. But being a concerned Indian and as a part of the Swachh Bharat Abhiyan, it is our utmost duty that the groundwater should not be polluted by any means or intensity of pollution of groundwater may be reduced.

15.6.1 Phytoremediation

Phytoremediation is one effective method to achieve this goal. This method involves the use of living plants to extract contaminants from groundwater by their interaction with the hydrological system. Simply the entry of contaminants into the plants is like more than half of the work is done. Thereafter the living plants volatilize the

Table 15.10 Heavy metals contamination in groundwater of some states of India

Place	Cd	Cu	Co	Cr	Mn	Pb	Fe	Zn	References
Tamil Nadu									
Chennai	0.13	***	0.05	***	***	0.1	0.06	0.3	Rajan and Ponni (2013)
Pondicherry	***	0.04	***	0.06	0.09	0.08	0.46	***	Jameel et al. (2012)
Odisha									
Sukinda valley	***	1.8	***	0.42	***	***	0.39	***	Dhakate and Singh (2008)
Assam									
Kamrup (Assam)	0.42	***	0.18	***	1.28	0.2	***	1.31	Chakrabarty and Sarma (2011)
Rajasthan									
Kota (2006)	***	0.09	***	0.07	0.08	0.1	0.23	0.1	Gupta et al. (2011)
Sri Ganganagar	1.32	0.35	***	***	***	0.14	***	5.2	Duggal et al. (2014)
Hanumangarh	6.9	0.56	***	***	***	0.17	***	2.4	
Churu	0.95	0.73	***	***	***	0.11	***	11.2	
Sikar	0.85	0.43	***	***	***	0.17	***	23.6	

***Data not reported

Table 15.11 Traces of different pesticides in different regions of India

Place	DDT (μg l^{-1})	Endosulfan (μg l^{-1})	Chloropyriphos (μg l^{-1})	Parathion methyl (μg l^{-1})	HCH (μg l^{-1})	Dichlorvos (μg l^{-1})	Organochlorine (μg l^{-1})	Organophosphate (μg l^{-1})	References
Maharashtra									Lari et al. (2014)
Yavatmal	–	0.78	0.21	–	–	–	–	–	
Amravati	–	0.42	0.11	0.09	0.39	0.08	–	–	
Bhandara	–	0.72	0.25	003	0.06	0.09	–	–	
Kerala									Akhil and Sujatha (2012)
Panathur	–	58	–	–	–	–	–	–	
Periya	–	37	–	–	–	–	–	–	
Panathady	–	56	–	–	–	–	–	–	
Rajapuram	–	40	–	–	–	–	–	–	
Haryana									Thakur et al. (2015)
Ambala	848.2	27.4	–	–	87.6	–	–	–	
Gurgaon	275.3	164.2	–	–	99.8	–	–	–	
Hisar	115.9	53.0	–	–	78.5	–	–	–	
Delhi									Kaushik et al. (2012)
Yamuna Khadar region	–	–	–	–	–	–	0.293 to1.462	0.159 to 39.90	

absorbed contaminants to the atmosphere, or they degrade them into harmless compounds within their tissues.

However, phytoremediation cannot be applied universally. There are certain limitations in phytoremediation to make use of it. One main limitation is the variation between the depth of groundwater and the root length of living plants. Obviously, the roots of the plants cannot reach groundwater at deeper levels. Despite these constraints, the living plants whose roots go 15–20 feet below land surface will effectively serve the purpose. It is worth noting that mature poplar trees can pump out huge quantities of groundwater on a daily basis (Chappell 1998). Phytoremediation takes place through several mechanisms.

- **Phyto-accumulation:** In this, plants absorb and store contaminants in plant tissues. Hyperaccumulators, as the name itself reveals, draw contaminants and store them far above the normal limits.
- **Phyto-volatilization:** This mechanism involves uptake of water along with contaminants and passing through the xylem and eventually vaporizing them into the atmosphere through the foliage.
- **Phyto-degradation:** Plants absorb, assimilate and then degrade contaminants into a less toxic state. The degradation process happens during metabolic processes aided by certain enzymes.
- **Phyto-stabilization:** Plants immobilize contaminants at the interface of roots and soil by producing chemical compounds.

Very limited research work has been done on phytoremediation of contaminated groundwater in India. However, some of the findings of the research work that has been done in India are given below:

Salix acmophylla serves dual purpose of bio-monitoring and phytoremediation of heavy metals like Ni, Cu and Pb in Lake Nainital in Uttar Pradesh, India (Ali et al. 1999). A study in Pariyej reservoir, a community reserve in Gujarat, India, by Kumar et al. (2008) has found out high accumulation of Cd (23.83 ppm) in *Ipomoea aquatica*, Co (25.75 ppm) and Zn (709.07 ppm) in *Eichhornia crassipes*, Cu (1617.21 ppm) and Ni (28.83) in *Nelumbo nucifera* and Pb (82.40 ppm) in *Vallisneria spiralis* and proposed these species as potential phytoremediators for these heavy metals. Ghosh (2010) reported that *Hydrilla verticillata* is a strong accumulator of As and Cd and *Ipomoea aquatica* as a potential accumulator of Cd. Findings of a research study (Rai 2008) on Hg pollution in industrial effluents from the Singrauli industrial belt in India showed that when *Azolla pinnata* was grown in the presence of Hg (II) ions at 0.5 mg l^{-1}, its growth saw a reduction by 27–33.9% compared to control. After 13 days of growth, Hg content in the growing medium decreased by 70–94%. *Typha angustifolia* and *Ipomoea carnea* were found to be very effective for removal of Pb from contaminated water on account of the fact that they accumulate Pb in roots (1200 and 1500 mg kg^{-1}, respectively) and shoots (275 and 425 mg kg^{-1}, respectively) at higher concentrations (Adhikari et al. 2010). *Typha angustifolia* was also found as potential phytoremediators of heavy metals like Zn, Cu and Ni contained in industrial wastewater (Chandra and Yadav 2010).

Kumar et al. (2012) conducted a study on phytoremediation of heavy metal using five native macrophytes, namely, *Eichhornia crassipes*, *Hydrilla verticillata*, *Bacopa monnieri*, *Marsilea minuta* and *Ipomoea aquatica* and found out that *Eichhornia crassipes* can be applied for removal of Cu and Ni and *Hydrilla verticillata* and *Marsilea minuta* can be used for removal of Pb and Cr, respectively, from polluted waterbodies. Tiwari et al. (2008) did an experiment with *Portulaca tuberosa* and *Portulaca oleracea* collected from sites irrigated with tube well and industrial wastewater in Gujarat. Both of these species have hyperaccumulated heavy metals (Cr, As and Cd) and remained unaffected in terms of biomass production and high regeneration capacity. For this reason, both these species are found to be suitable for phytoremediation of effluent contaminated areas. Of the plants – sunflower, Indian mustard, rye, spinach, tobacco and corn – sunflower was found to have the maximum ability for removal of Pb from effluents (Raskin and Ensley 2000). The biomass of *Aspergillus niger* was coated with iron oxide to find out the potential of As removal. While treated, thus, 95% of As(V) and 75 5 of As(III) were removed at a pH of 6 (Pokhrel and Viraraghavan 2006). *Garcinia cambogia* indigenous to India has been found to be quite useful for removal of As from groundwater (Kamala et al. 2005). It was found that water lettuce (*Pistia stratiotes*) has absorbed As ranging from 0.25 to 5 mg l^{-1} at pH of 7 after 144 h (Basu et al. 2003).

15.6.2 Microbial Remediation

Microbial remediation is process by which hazardous contaminants are degraded to safer levels through enzymatic activity in micro-organisms. The study of how micro-organisms respond to toxic heavy metals assumes added significance in view of its relevance to remediating contaminated groundwater. The reliance on microbes in the processes of effluent treatments is a usual practice. Micro-organisms that exist in the sludge of wastewater treatment systems break the toxic larger molecules into simple and smaller forms, thereby reducing the level of toxicity. Anaerobic, aerobic and facultative micro-organisms perform specific roles in the wastewater treatment systems. Metal uptake by micro-organisms can occur either actively or passively or in both ways. The applicability of biosorptive processes (passive) is greater than bioaccumulative processes (active) in large-scale systems. This is explicable by the fact that bioaccumulation requires more nutrients resulting in increased chemical and biological oxygen demand in the effluents. On the other hand, biosorption is cost-effective and environment-friendly and produces requisite effect in removing toxic elements from contaminated water (Rani et al. 2009).

Klebsiella pneumoniae is a useful bacterium to remediate heavy metals even at higher concentrations of 15 mM (Sharma et al. 2000). Studies have been conducted by Sanyal et al. (2005) on how fungus *Fusarium oxysporum* remediates aqueous Cd and Pb ions. During metabolic activity, carbon dioxide is released which in turn reacts with the heavy metal ions and forms metal carbonates. Prakasham et al. (1999) have demonstrated that in a stirred tank reactor at 1:10 biomass liquid ratio, 85–90% of Cr is adsorbed in nonliving biomass of *Rhizopus arrhizus* at a pH of 2 for 4-h contact time. But in a fluidized reactor, 94% of Cr is adsorbed. For the effective removal of heavy metals like Pb, Zn, Mn, Fe and Cu by *Pseudomonas fluorescens* and *Pseudomonas aeruginosa*, the pH and temperature of paper mill effluent have to be optimized to 7–9 and 25–35 °C (Paranthaman and Karthikeyan 2015). Sunil et al. (2015) identified 12 bacterial isolates tolerant to Hg and Pb from paddy fields irrigated with industrial effluents in suburban Mysore, Karnataka, India. Among them *Streptomyces flavomacrosporus* was found to be a good bioremediator with higher growth rate even at high levels of metal concentration. Priyalaxmi et al. (2014) reported a bacterial strain RSA-4 from a marine bacterium *Bacillus safensis* for remediation of Cd by means of phylogenetic analysis. Manoharan and Subramaniam (1992) used *Oscillatoria psebdigenubata*, Cynobacterium, for the removal of nitrate from groundwater.

15.6.3 Chemical Remediation

The elements/ions that affect water quality at significant levels in India are fluoride, arsenic, iron and nitrates. There are certain chemical remediation techniques which are used in India to address these problems. There are mainly two methods to remove fluoride from water, namely, adsorbent and coagulant. Adsorbent technique makes use of activated alumina and activated carbon. A lot of non-governmental organizations in India’s rural area propagate activated alumina method for providing safe drinking water with funds made available by UNICEF/other agencies. In the state of Rajasthan, a specially designed 20 litre bucket is provided to the beneficiaries. A microfilter containing 5 kg of activated alumina forms part of the bucket. This cost-effective method removes up to 90% fluoride (Meenakshi and Maheshwari 2006). The principally used coagulants are lime and alum. In the Nalgonda technique, lime is first added to the contaminated water, and this precipitates fluoride into insoluble calcium fluoride. However, the pH of water raises to 11–12, and a residue with 8 mg $F\,l^{-1}$ is formed. In order to overcome this negative fallout, alum is added (Nawalakhe et al. 1974; Technical Digest 1978).

For As removal, common coagulants used are iron, alum and lime. Even though these chemicals are purchasable from the market, they do not ensure removal of As in its entirety. Activated alumina, ion-exchange resin and iron-coated sand are commonly used adsorbents for remediation of As-contaminated water. From his study, Ghosh et al. (2003) have established that $FeCl_3$ is more efficient than $MgCl_2$ for the removal of As in drinking water. His study has shown that the ferric system removed 90% of As in a duration of 2–3 min at a pH level of 7.5 or still lower, whereas $MgCl_2$ has achieved only a lower removal rate and that too taking more time. Chakravarty et al. (2002) conducted a study to find out the efficiency of ferruginous manganese ore (FMO) in removing As from groundwater. He collected six groundwater samples containing As in the range between 0.04 and 0.18 ppm from North 24 Parganas, West Bengal, India. This FMO efficiently adsorbed both As (III) and As(V) in the pH of 2–8. It is noteworthy even at pH of 2, it resisted desorption.

Water contaminated with nitrate is passed through a strong base anion exchange resin beds – in the process an exchange between nitrate and chloride/bicarbonate takes place until the resin is exhausted. By using a solution of $NaCl_2$ and $NaHCO_3$, the exhausted resin can be regenerated (Kokufuta et al. 1988). When bentonite clay is added to the backwash water, restoration of exhausted resin can also take place (Kapoor and Viraraghavan 1997). Gaikwad and Warade (2014) found out that natural zeolite-stilbite were more effective in removing nitrate from groundwater compared to granular activated carbon but limited to maximum efficiency when initial nitrate concentration is 80 mg l^{-1}.

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Tree-based Systems for Enhancing Environmental Services of Saline Environments

16

S. R. Gupta, J. C. Dagar, R. Jangra, and Asha Gaur

Abstract

Nearly one billion hectares of arid and semiarid regions of the world are salt-affected. In India, saline and sodic soils occupy an area of about 6.75 Mha. Salt-affected lands can be utilized for producing food, fodder, timber, and fuelwood by incorporating trees with crops and forage grasses. Biodrainage has been successfully used to control the problem of waterlogging and salinity in irrigated areas. The tree-based systems for salt-affected lands include agri-silvicultural, silvopastoral agroforestry, fruit-based agroforestry systems, and trees for biodrainage, energy plantations, and agroforestry for dryland salinity. The tree-based systems have been found to improve the provisioning, supporting, and regulatory services. The provisioning services include genetic resources, food, energy, timber, fodder, and fresh water. The ability of soils to deliver the ecosystem services directly depends on soil regulatory services of soil biodiversity, decomposition, regulation of fluxes of greenhouse gases, and plant-soil nutrient cycles. Biodrainage is one of the important ecosystem services that could be provided by tree-based systems in saline and waterlogged soils. Agroforestry on salt lands provides environmental benefits like increase in biodiversity, salinity mitigation, biodrainage, and pollination in addition to carbon sequestration. Salt-affected soils have the potential to sequester carbon in the soil-plant system. In the southern Murray-Darling basin region of South Australia, carbon sequestration in plant biomass has been found to be significant, and the values ranged from 6.3 to 10.6 CO_2-e Mg ha^{-1} yr^{-1}. Soil carbon sequestration in different biosaline agroforestry systems in India is estimated to

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be 99.33–35.28 CO_2-e Mg ha^{-1}. This chapter presents an overview of environmental services of tree-based systems on saline, sodic, and waterlogged soils with special reference to carbon sequestration as a regulating ecosystem service and the role of agroforestry in soil bioamelioration as well as climate change mitigation.

16.1 Introduction

Salt-affected soils are reported to occur mainly in the arid and semiarid regions of the world, and their extent is about 932.2 million hectare globally (Szabolcs 1989). These soils have developed both by natural processes and anthropogenic activities. Salt-affected soils that occur naturally on drylands are highly saline or sodic because of severe constraints of vegetation and tree cover which are sparse and scarce. Anthropogenic salt-affected soils have developed due to faulty irrigation in canal command area and poor drainage and irrigation with saline or/and sodic waters. The problems of secondary salinization, alkalization, and waterlogging have increased because of the excessive irrigation in agriculture (Szabolcs 1994; Rengasamy 2006; Qadir et al. 2007). Globally, 10% of irrigated land is affected by salinity; the pressures vary significantly both in time and space (Tanji and Kielen 2002). Waterlogging and salinity are major environmental stresses for the long-term sustainability of irrigated lands and livelihood of the farmers, especially the smallholders both in canal-irrigated and nonirrigated regions. Because of salinity and sodicity problems, crop yields are reduced, and the provision of environmental services is poor, thus affecting the livelihood of people dependent on soil and water resources of marginal lands (Qadir et al. 2007).

The cost of lost crop production due to salt-induced land degradation in irrigated areas has been estimated to be around 27.3 billion US dollars (Qadir et al. 2014). The key ecosystem services such as the maintenance of soil fertility, carbon sequestration, biomass production, and the regulation of soil water flows are important for the utilization and management of salt-affected lands. Analyzing plant biomass production and estimating the rates of carbon sequestration (Lal 2004) and exploration of greenhouse gas balance (Wicke et al. 2013) provide useful strategies to understand the potential of tree-based systems for climate change mitigation on marginal lands. The impact of soil salinity and other soil degradation processes on ecosystem services of agricultural landscapes need to be analyzed (MEA 2005; Holland et al. 2015).

Ecosystem functions provide goods and services that satisfy human needs, directly or indirectly (De Groot et al. 2002). The environmental services are the benefits that the natural environment provides to humanity. There are four major types of ecosystem services, i.e., provisioning services, regulating services, cultural services, and supporting services that contribute to human well-being (MEA 2005). It is estimated that 60% of the earth's ecosystem services have been degraded in the past 60 years due to the impact of human activities (MEA 2005). Agroforestry can increase biodiversity on degraded salt lands by enhancing numerous ecological and production functions. Ecosystem service provisions have been found to occur at multiple scales, for example, carbon sequestration for climate regulation at the global scale and the maintenance of soil structure and fertility at the local scale (MEA 2005).

The salt-affected lands can be brought under viable vegetation cover by using suitable planting techniques and making use of salt-tolerant plant species. Soil rehabilitation by the use of suitable agroforestry systems is an effective way to both productively utilize and desalinize salt-affected lands (Vargas et al. 2018). The main services from tree plantations and agroforestry systems include the various provisioning, regulatory and supporting services (Jose 2009; Montagnini and Nair 2004; Nair et al. 2009; Jose and Bardhan 2012), and climate change mitigation and adaptation (Nair 2012). The services and benefits provided by agroforestry practices occur over a range of spatial and temporal scales (Izac 2003; Jose 2009). The improvement of soil carbon in agroforestry systems on salt-affected lands is of particular interest from the point of view of global climate change mitigation (Wicke et al. 2013). In the Murray-Darling basin, land-use changes have caused the salinization of rainfed (Charman and Murphy 2007) as well as the irrigated land (Tanji and Kielen 2002). In Murray-Darling basin of Australia, ecosystem services and management response as influenced by salinity have been analyzed by only a few workers (Holland et al. 2015).

The objective of this chapter is to give an overview of environmental services of tree-based systems on salt-affected lands with special reference to carbon sequestration as a regulating ecosystem service and the role of agroforestry in soil bioamelioration and climate change mitigation.

16.2 Salt-induced Land Degradation

There are variable estimates for the global area of salt-affected land depending on the datasets, and the classification systems used (Szabolcs 1989; FAO 2001, 2008). Recent estimates show that approximately one billion hectares of land are salt-affected worldwide (Wicke et al. 2011), of which about 76 million hectares (Mha) are affected by human-induced salinization and sodification (Oldeman et al. 1991). Salt-affected soils have been reported to occur within at least 75 countries in different parts of the world (Qadir et al. 2014). In India, about 6.75 Mha lands are either sodic or saline (Mandal et al. 2010). In Pakistan, nearly 6.3 million ha of land are affected by different levels and types of salinity, out of which nearly half are under irrigated agriculture, especially in Indus basin (Qureshi et al. 2008). The occurrence of salt-affected soils is predicted to increase under conditions of climate change due to increasing aridity (Amini et al. 2016).

Salt-affected lands in Central Asian region are the most characteristic features of natural continental terrestrial salinization, sodication, and alkalinization (Toderich et al. 2013). These soils are unproductive because of their low organic matter (<1.0%), high salt contents, and poor water-holding capacity (Toderich et al. 2013). In the San Joaquin Valley in the United States, salt buildup in the soils and groundwater is threatening the productivity and sustainability of otherwise highly productive lands (Schoups et al. 2005).

In Australia, land clearing for agriculture removed the original native vegetation, which gave rise to dryland salinity, because of a rising saline water table, affecting over 90% of the agricultural lands (Stirzaker et al. 2002). It has been estimated that at least 180,000 ha of north-southwest of Australia is currently affected by dryland salinity or has shallow water tables less than <2 m deep (Johnson et al. 2009). Dryland salinity is characterized by the presence of salts in the soil or groundwater because of anthropogenic land-use change (see Holland et al. 2015). Irrigation-induced salinity occurs because excess water applied to crops travels beyond the root zone to groundwater resulting in the rise of the water table and salt buildup in the surface layer of soil.

Salt-affected soils are generally categorized into saline, alkaline/sodic, and saline-sodic soils. The saline soils are characterized by the presence of white encrustations on the soil surface and have high concentrations of soluble chlorides and sulfates of sodium, calcium, and magnesium. The sodic soils are characterized by high soil pH (saturation soil paste pH > 8.5 and often approaching 11), high exchangeable sodium percentage (ESP)>15 and varying electrical conductivity (ECe < 2–4 dS m^{-1}), and low soil organic matter. The precipitation of calcium in alkali soils causes deposition of thick $CaCO_3$ layer in the soil profile which is known as *kankar* pan.

The saline- sodic soils are characterized by high levels of soluble salts as well as sodium ions. Some salt-affected soils are also affected by magnesium (Vyshpolsky et al. 2008), when plowed, these soils form large clods that impede water flow resulting in poor water distribution and plant growth.

The soils are considered waterlogged or potentially waterlogged, when the water table reaches within 1.5–2 m of the ground surface. Waterlogged soils can be saline, saline-sodic, and sodic soils. In the case of dryland salinity, rising groundwater mobilizes salt stored in the soil profile into the root zone of plants and trees and concentrating at the soil surface through evaporation (see Stirzaker et al. 2002). Characteristics of salt-affected soils are discussed in detail elsewhere in this book.

16.3 Tree-based Systems for Salt-affected Lands

On the basis of data compiled by Gupta and Dagar (2016), the tree-based systems for salt-affected lands are comprised of agri-silvicultural, silvopastoral agroforestry, fruit-based agroforestry systems, trees for biodrainage, energy plantations, halophytic trees to remediate soil, and agroforestry for dryland salinity (Table 16.1). Agri-silvicultural systems on a moderately alkali soil in northwestern India (pH 9.2) were developed by planting three timber tree species, namely, poplar (*Populus deltoides*), eucalyptus (*Eucalyptus tereticornis*), and *Acacia nilotica* in association with cropping systems of rice-wheat, rice-Egyptian clover, and pigeon pea/sorghum-mustard rotations, whereas sole trees and sole crops served as control (Singh et al. 1997). An agri-silvicultural trial of trees intercropped with deep-rooted, early

Table 16.1 Some tree-based systems on salt-affected lands in India, Central Asia, and Western Australia (GW = ground water) [based on (Gupta and Dagar 2016) and other sources]

Saline environments	Agroforestry system, role of trees	Study areas, reference
Moderately alkali soil	Agrisilviculture – *Populus deltoides*, *Eucalyptus tereticornis*, and *Acacia nilotica* with crops	CSSRI, Karnal, India
		Singh et al. (1997)
Reclaimed sodic soil	Tree plantation of *Grevillea robusta*	CSSRI, Karnal, India
	Carbon sequestration	Jangra et al. (2010)
Moderately alkali soil	Age-old agrisilviculture system of *Eucalyptus tereticornis* with sugarcane and wheat crop	Salimpur, Haryana, India
	Timber, Fuel wood, Carbon sequestration	Gaur (2013)
Degraded, saline lands	Agrisilvicultural system – *Tamarix*, *Elaeagnus angustifolia* with legume crop	Central Asia
	Fuelwood production and restoration	Toderich et al. (2013)
Sodic soil, presence of precipitated $CaCO_3$ layer at various soil depths	Silvopastoral agroforestry systems, tree species of *Acacia nilotica, Dalbergia sissoo,* and *Prosopis juliflora* along with salt-adapted grasses	Bichian, Haryana, India
	Timber, fuel wood, and carbon sequestration	Kaur et al. (2002a, b)
Clay loam saline vertisol	Silvopastoral systems with *Salvadora persica* with grass species of *Leptochloa fusca*, *Eragrostis* sp., and *Dichanthium annulatum*	Gujarat, India
		Rao et al. (2003)
Saline water irrigated semiarid soils	Silvopastoral system of *Acacia nilotica, Salvadora persica* with native grasses	Hisar, Haryana, India
	Carbon sequestration	Kumari et al. (2018)
Saline water irrigated semiarid hyperthermic camborthids soils	Fruit-based agroforestry systems, tree plantations	Hisar, Haryana, India
	Fruit production, carbon sequestration	Dagar et al. (2016a) and Dagar (2018)
Moderate alkali soils	Agroforestry based on medicinal and aromatic crops	CSSRI, Karnal, India
		Dagar et al. (2009)
Saline-sodic topsoil, sodic subsoils, waterlogged	Agroforestry for water-logged areas	Puthi, Haryana, India
	Biodrainage, Carbon sequestration	Ram et al. (2007) and Kumar (2012)

(continued)

Table 16.1 (continued)

Saline environments	Agroforestry system, role of trees	Study areas, reference
High soil sodicity with calcareous hard pans + fresh Ground water	Energy plantation with *Jatropha curcas*, a biodiesel plant	Lucknow, India Singh et al (2013)
Dryland salinity, water tables 1–3 m belowground, salinity 500–3000 mS/m	Agroforestry for dryland salinity, saline alley farming	Narrogin, Western Australia Stirzaker and Lefroy (1997)
Dryland salinity	Agroforestry system with alley cropping of wheat; alley farming; short rotation farming	South-west; Western Australia

maturing, and frost-tolerant legume was established for utilizing degraded, saline lands in northern Tajikistan (Toderich et al. 2013).

The sodic soils have been improved by adopting reclamation forestry and agroforestry (Singh and Gill 1992; Singh 1995). On highly sodic soils at Bichhian, northwestern India, the silvopastoral agroforestry systems were comprised of tree species of *Acacia nilotica*, *Dalbergia sissoo*, and *Prosopis juliflora* along with the naturally salt-adapted grass species of *Desmostachya bipinnata* and *Sporobolus marginatus* (Kaur et al. 2002a, b), Table 16.1.

The fruit species which can be established successfully in alkali soils are *Ziziphus mauritiana*, *Psidium guajava*, *Punica granatum*, and *Syzygium cuminii*. After a sufficient time, the crops can also be grown as agrihorticultural system. Saline water (ECiw up to 10 dS m^{-1}) could be used for establishing these fruit trees and irrigating the component crops without significant salinity buildup in sandy loam calcareous soils in northwestern India (Dagar et al. 2016a). On the basis of a long-term study, it was found that the fruit-based agro-forestry systems could be successfully developed with saline groundwater irrigation on calcareous soil for supporting sustainable crop and fruits production (Dagar et al. 2016a).

Matricaria chamomilla, *Catharanthus roseus*, and *Chrysanthemum indicum* were reported to be interesting medicinal and flower-yielding plants which could be grown on moderate alkali soil (Dagar et al. 2009). All these medicinal plants could be integrated suitably as intercrops in agroforestry systems either with forest trees or fruit trees on moderate alkali soils. In the Steppes in Uzbekistan, the highly saline abandoned soils have been restored by growing a salt-tolerant perennial shrub species of licorice (*Glycyrrhiza glabra*) (Kushiev et al. 2005).

Much of the world's saline land is also subject to waterlogging due to the presence of shallow water tables or decreased infiltration of surface water due to sodicity (Ghassemi et al. 1995; Qureshi and Barrett-Lennard 1998). Biodrainage may be defined as "pumping of excess soil water by deep-rooted plants using their bio-energy" (Ram et al. 2008). The *Eucalyptus*-based agroforestry on waterlogged soils has been found to be promising in the semiarid regions of Haryana (Ram et al. 2007, 2008; Kumar 2012) (Table 16.1).

Alley cropping and parkland agroforestry have been developed for managing dryland salinity (Lefroy et al. 1992; Lefroy and Scott 1994). A special feature of many dryland soils is salinity, either through natural occurrence or increasingly as a result of irrigation (Glenn et al. 1992). Many tree species like *Casuarina cunninghamiana*, *Eucalyptus argophloia*, *E. camaldulensis*, *E. melliodora*, *E. moluccana*, possibly *E. sideroxylon*, and *E. tereticornis* are reported to use water of EC 4–8 dS m^{-1}; some more salt-tolerant species like *E. occidentalis* and *Casuarina glauca* and *some provenances E. camaldulensis* are capable of using substantial amounts of saline groundwater (EC up to 16–20 dS m^{-1}) (Marcar and Crawford 2004). In areas of poorer drainage, very salt-tolerant species like *Casuarina obesa* and *Acacia stenophylla* can grow well in highly saline areas (ECe 8–16 dS m^{-1}) (Marcar and Crawford 2004).

16.4 Environmental Services of Tree-based Systems

The ecosystem services are the benefits that the natural environment provides to humanity. There are four broad categories of ecosystem services, i.e., provisioning, regulating, cultural, and supporting services (MEA 2005). The provisioning services relate to the processes that yield foods, fibers, fuels, water, biochemical, medicinal plants, pharmaceuticals, and genetic resources. The cultural services are largely nonmaterial benefits of the environment. The regulating services refer to benefits that result from regulation of ecosystem processes, including mainly soil stabilization, waste treatment, air quality maintenance, climate regulation, and hydrological flows. The supporting services are those that are necessary for the production of all other ecosystem services, and their impacts on people are indirect (MEA 2005). Supporting ecosystem services include biomass production, production of atmospheric oxygen, soil formation and retention, nutrient cycling, and provision of habitat.

The tree-based systems influence provisioning, supporting and regulatory services on sodic, saline, and waterlogged soils (Fig. 16.1). The tree-based systems have significant impact on plant and soil biodiversity underpinning many ecosystem services. Tree-based systems have favorable effect on soil properties and processes, which play an important role in climate regulation through carbon sequestration and reducing greenhouse gas emissions and provision of water through regulation of soil properties. The ecosystem services can provide a framework for analyzing the differences in specific ecosystem services among soil types and interconnections between the ecosystem services and key soil processes (Palm et al. 2007). The agroforestry systems and tree plantations on salt-affected soils have been found to enhance various environmental services of these marginal lands (Gupta et al. 2016).

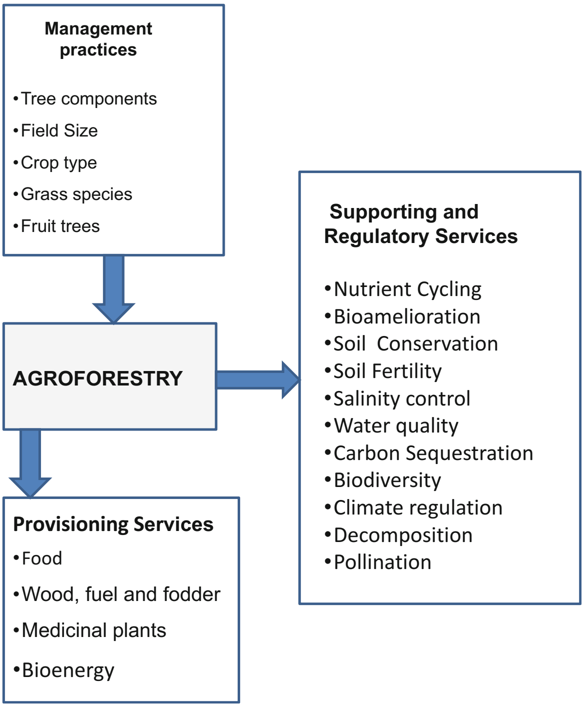

Fig. 16.1 The potential ecosystem services of agroforestry in saline environment

16.4.1 Provisioning Services of Tree-based Systems

The provisioning services of the agroforestry systems include genetic resources, food, energy, timber, fodder, and fresh water. These provisioning services give economic and social benefits and are readily appropriated by the local people. If the trees are used as fodder or as shade trees, they can be planted scattered over the fields that can be used as pastures but can also be planted in blocks or as timber belts. The trees can be directly browsed by cattle or the leaves, and pods can be harvested to feed cattle.

16.4.1.1 Food, Timber, Fodder, and Fuelwood Production

In *Acacia*-, *Eucalyptus*-, and *Populus*-based agroforestry systems, there was improvement in biological production due to improvement of soil organic matter and availability of soil inorganic nitrogen (Singh et al. 1995, 1997). The crops of Egyptian clover, rice, wheat, and mustard could successfully be grown in the agrisilvicultural systems during the initial 3 years. After 3 years, these crops planted initially were replaced with shade-loving turmeric (*Curcuma longa*). Irrigation of these intercrops helped *Populus* and *Eucalyptus* grow faster but adversely affected the growth of low water demanding trees like *Acacia*. In different agroforestry systems, soil amelioration measured in terms of decrease in pH and improvement in organic carbon and available N, P, and K contents followed the order: *Acacia*-based system > *Populus*-based system > *Eucalyptus*-based system > sole crops. Among tree plantations, *Populus* was most profitable followed by *Acacia* and *Eucalyptus*. Thus, the agri-silvicultural systems on moderate alkali soils were found to be economically viable in terms of food, fodder, timber, and firewood production system as well as practicable for soil carbon sequestration in the long term (Singh et al. 1997).

On moderately alkali soils at Salimpur (Kurukshetra) in northern India, sugarcane (*Saccharum officinarum*) was grown during first and second year of tree growth, and wheat crop was grown during the Kharif season (November to April) in interspaces between the rows of planted trees in 3- to 6-year-old agroforestry systems (Fig. 16.2). The biomass of tree components in 16-year-old *Eucalyptus tereticornis* (clonal) agroforestry systems was 15.534–59.01 Mg ha^{-1} bole and 1.461 and 9.199 Mg ha^{-1} branches (Table 16.3). At the time of crop harvest, the biomass accumulation in the sugarcane was 24.13 Mg ha^{-1} and 23.794 Mg ha^{-1} in 1- and 2-year-old agroforestry systems, respectively (Gaur 2013). The cane production of sugarcane varied from 14.808 to 14.513 Mg ha^{-1}. The biomass accumulation in wheat crop was 9.170 Mg ha^{-1} to 7.984 Mg ha^{-1} in 3- to 6-year-old agroforestry systems. Biomass accumulation in wheat crop was found to be slightly higher in the shoots as compared to grains. The grain yield of wheat varied from 3.890 to 3.426 Mg ha^{-1} when grown in combination with the trees. The grain production decreased by 3.22%, 7.33%, and 11.93% in 4-, 5-, and 6-year-old agroforestry

Fig. 16.2 A general view of 1- to 4-year-old *Eucalyptus tereticornis* agroforestry systems on moderately alkali soils at Salimpur, Kurukshetra, northern India (Photo Dr SR Gupta and A Gaur)

Table 16.2 Biomass (Mg ha^{-1}) in different tree components, and grain/cane and straw production in wheat and sugarcane crops in 1-to 6-year-old *Eucalyptus tereticornis* (clonal) agroforestry systems of on moderately alkaline soil at Salimpur, Kurukshetra (Based on Gaur 2013)

	Plant biomass (Mg ha^{-1})					
Plant component	1 year	2 years	3 years	4 years	5 years	6 years
Tree bole	15.534	24.855	34.154	41.35	51.055	59.009
Tree branches	1.461	2.686	4.055	5.195	6.618	7.984
Crop grains/cane	14.81	14.51	3.89	3.765	3.605	3.426
Crop straw	1.392	1.386	4.915	4.811	4.712	4.426

systems, respectively, as compared to 3-year-old *Eucalyptus* systems (Gaur 2013) (Table 16.2).

In arid regions of northwestern India, *Prosopis cineraria* at the age of 12 years produced utilizable biomass of 19.1, 15.8, and 10.3 Mg ha^{-1} and dry leaf weight of 0.85, 0.67, and 0.50 Mg ha^{-1} at tree densities of 417, 278, and 208 trees ha^{-1}, respectively (Singh et al. 2007). The wood is a good fuel having calorific value of 5000 kcal kg^{-1}. Leaves of *Prosopis cineraria* are good forage with 12–18% crude protein (CP), while the pods contain 10–13% CP; the leaves and pods are consumed by all livestock species.

Salt-tolerant tree plantations and forage grasses could be raised using saline water irrigation (Minhas et al. 1997a, b; Tomar and Minhas 1998). After 9 years of planting on saline soils, *Acacia nilotica*, *Prosopis juliflora*, and *Casuarina glauca* were best suited to saline conditions; the aboveground biomass was 52–98 Mg ha^{-1} (Tomar and Minhas 1998) (Fig. 16.3). It is possible to grow salt-tolerant tree plantations and forage grasses using saline water irrigation (Minhas et al. 1997a, b; Tomar and Minhas 1998; Tomar et al. 2003a, b).

Silvopastoral agroforestry on highly sodic soils can provide significant amounts of timber and fuelwood, which improve local well-being by providing small timber and fuelwood on marginal salt lands. In silvopastoral agroforestry systems of *Acacia nilotica* + *Desmostachya bipinnata*, *Dalbergia sissoo* + *Desmostachya bipinnata*, and *Prosopis juliflora* + *Desmostachya bipinnata*, the bole wood that can be used as timber was 4.62–9.78 Mg ha^{-1}, and branch biomass production varied between 4.16 and 20.82 Mg ha^{-1} year^{-1} (Kaur et al. 2002a), (Fig. 16.4). Timber and fuelwood biomass in clonal *Eucalyptus tereticornis* plantation in different spacing showed timber production of 13.5–141.7 Mg ha^{-1}in shallow water table areas (Kumar 2012; Dagar et al. 2016b).

Salvadora persica-based silvopastoral system has been developed with forage grasses (*Leptochloa fusca*, *Eragrostis* sp., and *Dichanthium annulatum*) on clay loam saline vertisol (ECe being 25–70 dS m$^{-1)}$ in Gujarat (Rao et al. 2003). *Leptochloa fusca*, *Eragrostis* sp., and *Dichanthium annulatum*, when planted on 45 cm high ridges, could produce 3.17, 1.85, and 1.09 Mg ha^{-1} forage, respectively. When planted in furrows, the forage yield was 3.75, 1.76, and 0.54 Mg ha^{-1} in the case of *Leptochloa fusca*, *Eragrostis* sp., and *Dichanthium annulatum,* respectively, showing their potential for these highly degraded lands. These grasses absorbed

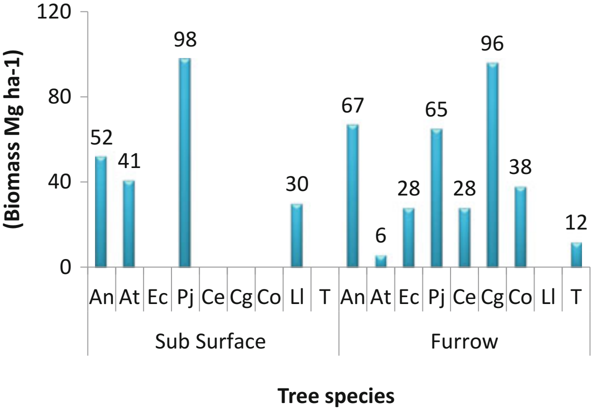

Fig. 16.3 Aboveground biomass of trees after 9 years of planting on saline soils. *An, Acacia nilotica; At, A. tortilis; Ec, Eucalyptus camaldulensis; Pj, Prosopis juliflora; Ce, Casuarina equisetifolia; Cg, C. glauca; Co, C. obesa; Ll, Leucaena leucocephala; T, Tamarix* sp. (Based on Tomar and Minhas 1998)

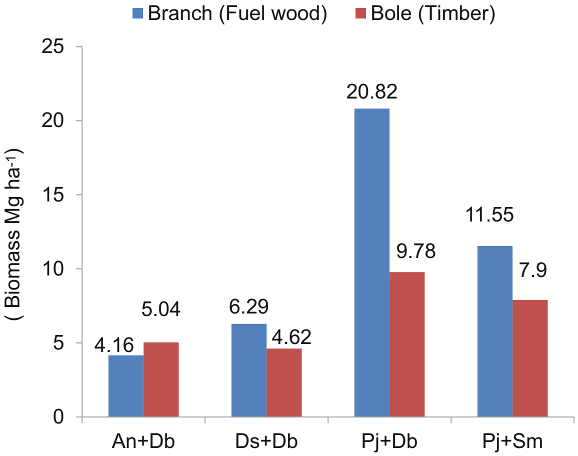

Fig. 16.4 Timber and fuelwood production in silvopastoral systems of *Acacia nilotica* (An), *Dalbergia sissoo* (Ds), and *Prosopis juliflora* (pj) along with *Desmostachya bipinnata* (Db) and *Sporobolus marginatus* (Sm) on a sodic soil (From Kaur et al. 2002a)

large quantity of salt in their biomass which resulted in amelioration of the soil to great extent by reducing the ECe value of the soil (Rao et al. 2003).

Lamers et al. (2008) and Lamers and Khamzina (2008) evaluated the prospects of establishing agroforestry systems on saline wastelands in the lower reaches of the Amu Darya River in Uzbekistan by using Russian olive (*Elaeagnus angustifolia*), Siberian elm (*Ulmus pumila*), and Euphrates poplar (*Populus euphratica*). The data collected for 5 years were compared with data of mature trees (15–20 years) growing naturally on the marginal land. It is interesting to note that the one ha plantation of *Populus euphratica* produced fuelwood to meet the average annual per capita energy needs of 89 people, followed by *Elaeagnus angustifolia* (72 people) and *Ulmus pumila* (55 people) (Lamers and Khamzina 2008), Table 16.3.

Table 16.3 Fuelwood production and their estimated energy value based on conversion into oil and coal equivalents for 5-year-old tree plantations (from Lamers and Khamzina 2008)

Capacity parameter	*Elaeagnus angustifolia*	*Ulmus pumila*	(*Populus euphratica*
Wood production (Mg ha^{-1})	25.5	19.8	32.0
Stem wood energy (MJ $tree^{-1}$)	118	118	117
Branch wood energy (MJ $tree^{-1}$)	94	43	145
Biofuel capacity (MJ ha^{-1})	487,623	369,886	601,036
Energy needs (people)	72	55	89

16.4.2 Supporting and Regulating Services of Tree-based Systems

The regulating services are the benefits obtained from regulation of ecosystem processes including soil stabilization and climate regulation to name only a few of these services (MEA 2005). The ability of soils to deliver the ecosystem services directly depends on soil regulatory services such as soil biodiversity, decomposition of organic materials, regulation of fluxes of greenhouse gases to and from the atmosphere, and plant-soil nutrient cycles (Palm et al. 2007).

16.4.2.1 Biomass Production

Salt-tolerant tree plantations and forage grasses could be raised using saline water irrigation (Minhas et al. 1997a, b; Tomar and Minhas 1998). Aboveground biomass of *Acacia nilotica Prosopis juliflora*, and *Casuarina glauca* on saline soils after 9 years of planting ranged from 52 to 98 Mg ha^{-1} (Tomar et al. 2003a, b). Thus, these tree species seem to be promising **as** energy plantations on both saline and sodic soils. Tree plantations of *Prosopis juliflora*, *Tamarix articulata*, and *Acacia nilotica* were found to be most suitable tree species for highly alkali soils both for biomass production and soil amelioration (Singh and Dagar 2005). Tomar et al. (2003b) and Dagar (2018) showed that when established with saline water (EC_{iw} up to 10 dS m^{-1}), *Acacia nilotica*, *Tamarix articulata*, *Acacia tortilis*, *Azadirachta indica*, *Feronia limonia*, *Prosopis juliflora*, and *Albizia lebbeck* are most suitable tree species for the dryland areas.

The Khorezm Region of Uzbekistan in Central Asia is affected by secondary salinization and depletion of soil nutrient stock. The productive capacity of these degraded lands could be improved by afforestation using tree plantations of *Elaeagnus angustifolia*, *Populus euphratica*, and *Ulmus pumila* (Khamzina et al. 2009a). *Elaeagnus angustifolia* had the highest growth rates in the early stages (2003–2005), but dry matter production tended to stabilize at about 100 Mg ha^{-1} in the year 2006. *Populus euphratica* initially grew poorly; the trees accumulated about 120 Mg ha^{-1} biomass during the same period. The woody aboveground components contributed 40–70% of total plant biomass depending on tree age and species (Khamzina et al. 2009a). The contribution of leaf biomass accounted for 6–15% of the total tree biomass, being the greatest in the case of *P. euphratica*. *Ulmus pumila* showed about 30–35% of biomass in its roots and was found to be significantly higher as compared to that of other two species (Khamzina et al. 2009a).

The mallee agroforestry has been shown to be important strategy for ameliorating secondary salinity on dryland farms in Western Australia during the early 1980s (see Sudmeyer and Hall 2015). The various studies suggest that mallee eucalypts as a biomass tree crop could be profitable for farmers to diversify their revenue in terms of provision of plant biomass and carbon sequestration to relevant markets (Eady et al. 2009; Paul et al. 2013). Within appropriate agroclimatic zones and soil conditions, mallee eucalypts can be integrated into farms with least minimal disturbance to livestock and cropping enterprises (Farquharson et al. 2013). For the designing of integrated mallee agroforestry systems, the competition for water and nutrients between mallee trees and crops needs to be taken into consideration (Sudmeyer et al. 2012). For a long-term experiment at Esperance in Western Australia, the biological productivity of different systems followed the order mallee monocultures harvested on a rotation of 5 or more years > crop monoculture > mallee agroforestry (Sudmeyer and Hall 2015).

16.4.2.2 Salinity and Waterlogging Control

Within the irrigated land-use systems, secondary soil salinization is mainly responsible for the cropland degradation. Mitigating dryland salinization by reducing elevated groundwater tables via biodrainage (Marcar and Crawford 2004) is one of the important ecosystem services that could be provided by tree plantations and agroforestry systems. Biodrainage uses the transpiration capacity of trees to control the recharge or enhance the discharge of the shallow groundwater (Heuperman et al. 2002).

In low rainfall areas of Western Australia receiving <600 mm rainfall per year, alley farming consisting of belts of perennial trees or shrubs with traditional crops has been found as one of the options for reducing recharge and controlling dryland salinity (Stirzaker et al. 1999). Phase farming with tree crops using short rotations of 3–5 years could be an alternative to alley farming for reducing recharge and creating a dry soil buffer for the leakage under subsequent annual crop rotations (Harper et al. 2000a, b). Spatial patterns of soil water depletion by *Eucalyptus* spp. (*Eucalyptus horistes*, *E. kochii* ssp. *plenissima*, *E. loxophleba* ssp. *lissophloia*, *E. polybractea*) have been analyzed to assess the potential of tree belts and short rotation phase farming with trees for the reduction of groundwater recharge and salinity control at six locations across southwest Western Australia (Harper et al. 2012). These workers showed within 7 years of planting the *Eucalyptus* spp., the trees could exploit soil water to depths of at least 8–10 m, and the root systems were able to penetrate even the clayey subsoils characterized by high bulk densities.

The potential of alley cropping for managing deep drainage in a field experiment has been analyzed to compare water use, growth, and nitrogen cycling in conventional cropping, perennial grass-based pasture (*Chloris gayana*), and the fodder tree tagasaste (*Chamaecytisus proliferus* Link) in spaced rows in alley crop and alley fallow (Lefroy et al. 2001a, b). In this study, the tree-crop mixture was found to

Table 16.4 The management responses, specific DPSI components, and ecosystem services as affected by salinity threat in the Murray-Darling basin of Australia. Management responses classified as adaptive or mitigatory (adapted from Holland et al. 2015)

Ecosystem services	Management response	Management response type	DPSI target	Effect on ecosystem services
Water quality	Planting trees	Mitigative	Pressure (hydrology)	Decreasing salt load
Food production	Growing tolerant plants	Adaptive	Impact (salt sensitivity)	Increasing plant growth for crops or fodder
Soil quality	Protecting native vegetation	Mitigative	Pressure (hydrology)	Reducing spread of salinization
Timber production	Spatially planned reforestation	Mitigative	Pressure (hydrology)	Increasing timber production
Genetic resources	Establishing conservation areas	Mitigative	Driver (land use)	Maintenance of plant and animal genetic diversity

reduce drainage indicating that alley cropping could be useful for maintaining water balance (Lefroy et al. 2001a, b).

Holland et al. (2015) analyzed the association between ecosystem service and management response in relation to salinity pressure using a Driver-Pressure-State-Impact-Response (DPSRI) framework in the Murray-Darling basin of Australia (Table 16.4). The focus of study was on provisioning services including food production, timber and forest products and genetic resources, and regulating services (water quality, air quality, and soil quality). They classified responses as either adaptive or mitigatory. Adaptation refers to cope with a threat while still providing an adequate level of ecosystem services (Rounsevell et al. 2010). On the other hand, mitigatory responses are aimed to “improve” the state of the environment to a level that will maintain or improve ecosystem services (Holland et al. 2015). These workers stated that nature-based responses such as planting trees or protecting native vegetation may be suitable for several different ecosystem services to deal with the threats from salinity to agroecosystems in Murray-Darling basin of Australia.

Khamzina et al. (2006) analyzed the potential of nine multipurpose tree species for reducing saline groundwater tables in the lower Amu Darya River region of Uzbekistan. The performance of various tree species was evaluated on the basis of their water use characteristics, salinity tolerance, growth rate, and the production of fodder and fuelwood. This study showed that *Elaeagnus angustifolia* performed best for biodrainage, whereas *Populus* spp. and *Ulmus pumila* also showed good potential for biodrainage (Khamzina et al. 2006). On the contrary, the fruit species such as *P. armeniaca* and *Morus alba* were having low biodrainage capacity. On marginal irrigated cropland, the 2- to 4-year-old tree plantations of *E. angustifolia*, *P. euphratica*, and *U. pumila* showed average transpiration of 1250, 1030, and 670 mm, respectively.

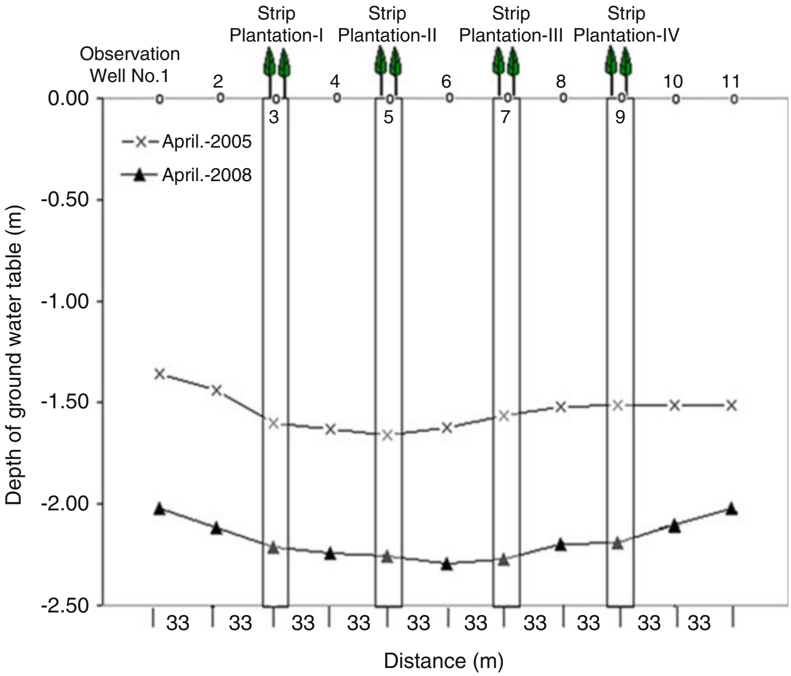

Fig. 16.5 *Eucalyptus* when planted in paired strips lowered the water table in the agricultural field in canal command area in Haryana to 85 cm in 3 years and below 2 m after 5 years of growth (Source: Ram et al. 2011; Dagar 2014)

The four strip plantations (spaced at 66 m and each having two rows of trees at 1 m × 1 m spacing in north-south direction) of 5-year- and 4-month-old clonal *E. tereticornis* worked as bio-pumps and lowered the water table located in canal command area with alluvial sandy loam soil in Haryana, India (Ram et al. 2011; Dagar 2014) (Fig. 16.5). The *Eucalyptus* plantations reclaimed waterlogged areas by lowering the water table, improving soil conditions, and increasing wheat grain yield by 3.4 times.

16.4.2.3 Soil Fertility Improvement and Bioamelioration

Revegetation of sodic wastelands in western Uttar Pradesh in India are reported to ameliorate soil conditions and improve soil biological activity (Tripathi and Singh 2005). After 40 years, the rehabilitated new forests caused significant soil amelioration of sodic soil in the Indo-Gangetic plains (Tripathi and Singh 2005). In these rehabilitated new forests, the soil amelioration was greatest in terms of total N, mineralized N, available N, and soil organic carbon. There was also significant reduction in exchangeable sodium percentage of the rehabilitated soils.

In northwestern India, trees such as *Terminalia articulata*, *Acacia nilotica*, *Prosopis juliflora*, and *Eucalyptus tereticornis* and several other tree species raised on saline water-irrigated calcareous soils enhanced the organic carbon contents of soils by >4.0 g carbon kg^{-1} soil in about 9 years of their growth (Tomar et al. 2003a, b).

In silvopasture agroforestry systems at Bichhian, northwestern India, there was large input of plant residue both from aboveground and belowground parts of trees and grasses into the soil resulting in the improvement of soil properties and fertility of highly sodic soils (Kaur et al. 2002a). The silvopastoral agroforestry systems on calcareous soils irrigated with saline water were characterized by tree species of *Acacia nilotica* and *Salvadora persica* along with native grasses of *Cenchrus ciliaris* and *Panicum miliare* (Kumari 2008). The litter accumulation on the ground floor in the two systems was *Salvadora persica* system (2.712 ± 0.154 to 3.682 ± 0.136 Mg ha^{-1}) and *Acacia nilotica* system (2.216 to 2.442 ± 0.135 Mg ha^{-1}). The carbon content in ground floor litter ranged from 1.108 to 1.841 MgC ha^{-1} being greater in the case of *Salvadora persica* silvopastoral system.

The energy plantation of *Jatropha curcas* after 6 years of its growth at Banthra Research Station, Lucknow, northern India, has been found to improve soil fertility and decrease soil sodicity (Singh et al. 2013). The various soil properties like soil bulk density, pH, electrical conductivity (EC), and exchangeable sodium percentage (ESP) decreased due to growth of plants in energy plantation. The soil amelioration potential of the energy plantation in terms of increase in soil organic carbon, nitrogen, microbial biomass, and various enzymatic activities was found to be significant when compared to initial soil properties at 0–15 cm soil depth (Singh et al. 2013).

In the lower Amu Darya River region of Uzbekistan, the conversion of degraded cropland to tree plantations improved soil total nitrogen stocks by 6–30% in 5 years in the upper 20 cm soil layer. The plant-available soil nitrogen was significantly greater in *Elaeagnus angustifolia* plantation as compared to that in *P. euphratica* and *Ulmus pumila* tree plantations. Increases in the concentrations of plant-available phosphorus by 74% suggest that tree plantations act as an efficient nutrient pump on degraded cropland (Khamzina et al. 2009b). Thus, N_2-fixing trees play significant role to improve in soil fertility. Afforestation with mixed-species tree plantations could possibly be a sustainable land-use option for the degraded cropland impacted by salinity (Khamzina et al. 2009b).

16.4.2.4 Nutrient Cycling

Nutrient cycling is a key ecosystem service that supports living organisms in diverse types of ecosystems. The various nutrient cycling processes include fixation of atmospheric nitrogen, phosphorus acquisition by mycorrhizal fungi from the soil unavailable pool, decomposition of organic matter, and nitrogen mineralization. The availability of nitrogen through biological nitrogen fixation by rhizobium and phosphorus supply by arbuscular mycorrhizal fungi is important nutrient cycling processes (dos Santos et al. 2010).

Soil improvement in agroforestry systems is linked to biological nitrogen fixation, recycling of nutrients from deeper layers to the surface soil, buildup of soil organic matter from aboveground and belowground parts of plants, increase in soil microbial activity, improvement in soil enzyme activity, and the enhanced activity of arbuscular mycorrhizal fungi.

Nitrogen Pool and Fluxes In a silvopastoral systems in a highly sodic soil showed that nitrogen pool in vegetation was 32.47% and 29.52% of the soil pool in *Prosopis juliflora*+ *Desmostachya bipinnata* and *Prosopis juliflora*+ *Sporobolus marginatus* silvopastoral system, respectively (Kaur et al. 2002a). The litterfall formed a major pathway of the return of nitrogen to the soil that amounted to 0.075–0.14 Mg N ha^{-1} $yr^{-1.}$ The turnover of fine root biomass in these systems also returned 0.019–0.037 Mg N ha^{-1} yr^{-1} to the soil. The return of total nitrogen from litterfall and fine roots to soil amounted to 0.11–0.177 Mg N ha^{-1} $yr^{-1.}$ Total nitrogen uptake by the trees and grasses was 0.156–0.277 Mg N ha^{-1} yr^{-1}. Thus, nitrogen sequestration in the system was 28.84–36.10% of total uptake of the nitrogen in the agroforestry systems (Kaur et al. 2002a). It is reported that P. *juliflora* can also fix atmospheric nitrogen through symbiosis due to the occurrence of the cowpea-type *Rhizobium.* The roots of predominant grasses in the silvopastoral systems also form mycorrhizal associations with arbuscular mycorrhizal fungi.

Soil Microbial Biomass and Nitrogen Mineralization Soil microbial biomass is a labile fraction of soil organic matter comprising 1–3% of total soil organic matter (Jenkinson and Ladd 1981) and plays a key role to conserve nutrients for plant growth in seasonally dry tropical forest ecosystems (Singh et al. 1989). The tree plantations and silvopastoral agroforestry systems raised on sodic soils have a marked effect on the quantity and quality of organic matter, which in turn regulates the levels of soil microbial biomass. In salt-affected soils, the size and dynamics of soil microbial biomass carbon pool have been found to vary with land-use type (Kaur et al. 2000) and tree species (Kaur et al. 2002b). It was interesting to find a significant relationship between microbial biomass carbon and plant biomass carbon ($r = 0.92$) as well as the flux of carbon in net primary productivity ($r = 0.92$). Nitrogen mineralization rates were found greater in silvopastoral systems compared to sole grass system. Soil organic matter was positively correlated with microbial biomass carbon, soil nitrogen, and nitrogen mineralization rates ($r = 0.95$–0.98, $p < 0.01$) (Kaur et al. 2002b).

In energy plantation, soil amelioration occurred due to growth of *Jatropha curcas* for 6 years on sodic soils. There was significant increase in soil organic carbon (SOC), nitrogen (N), phosphorus (P), soil microbial biomass (MB-C, MB-N, and MB-P), and enzyme activities (dehydrogenase, glucosidase, and protease) beneath the canopy of *Jatropha curcas* than outside the canopy (Singh et al. 2013), Fig. 16.6.

Arbuscular Mycorrhizal (AM) Fungi and Nutrient Cycling AM fungi regulate some of the key processes driving the carbon cycle and also mediate soil C storage (Rillig 2004; Verbruggen et al. 2013; Mohan et al. 2014; Verbruggen et al. 2016). In fact, AM fungi are reported to receive about 37–47% of belowground net primary production in ecosystems having the prevalence of AM host plants (Harris and Paul

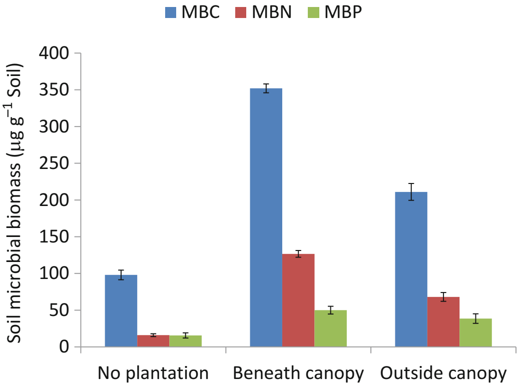

Fig. 16.6 Soil microbial biomass in *Jatropha curcas* energy plantation (Based on Singh et al. 2013)

1987; Johnson et al. 2002; Treseder and Cross 2006). AM fungi can enhance the removal of CO_2 from the atmosphere by plants and then depositing a part of the additional carbon into the soil. Mycorrhizal fungi are reported to sequester large amounts of C in living, dead, and residual hyphal biomass in the soil and may be mediating soil carbon sequestration (Treseder and Allen 2000).

Desmostachya bipinnata and *Sporobolus marginatus* are salt-adapted grasses, which showed moderately high diversity of arbuscular mycorrhizal (AM) fungi in their rhizosphere growing on sodic soils (Jangra et al. 2011). The arbuscular mycorrhizal species belonging to *Glomus* and *Acaulospora* have been found to dominate the AM fungal species occurring in the rhizosphere of these salt-adapted grasses. The density of arbuscular mycorrhizal (AM) fungal spores in soil of the sodic grassland systems was 0–15 cm soil depth, 22.8–60.8/g soil, and 15–30 cm soil depth, 9.6–18.4/g soil. Arbuscular mycorrhizal root colonization of *Sporobolus marginatus* growing on sodic soil (Jangra 2010) and *Panicum miliare* growing on saline water irrigated soils (Kumari 2008) showed the formation of arbuscules in cortical cells and presence of round and globose vesicles with attached hyphae (Fig. 16.7).

In *Acacia nilotica* and *Salvadora persica* silvopastoral system on saline-sodic soils, the AM root colonization in various grass species was observed to vary from 47.8% to 71.2% (Kumari 2008). In the agrihorticulture system of *Carissa carandas* along with *Hordeum vulgare*, some 23 species of mycorrhizal fungi belonging to *Glomus*, *Acaulospora*, and *Gigaspora* were recorded. The AM fungal species belonging to *Glomus* were more prevalent. The commonly occurring AM fungal species were *Glomus macrocarpum*, *Glomus caledonium*, *Glomus constrictum*, *Glomus pallidum*, *Glomus mosseae*, *Glomus intraradices*, *Glomus reticulatum*, and six unidentified species. In the silvopastoral system and the agrihorticulture system, the spore density in the rhizosphere of predominant grasses varied from 57.6 to 203.2 spores/10 g soil, the value being greatest in the case of *Hordeum vulgare* (Kumari 2008), Table 16.5.

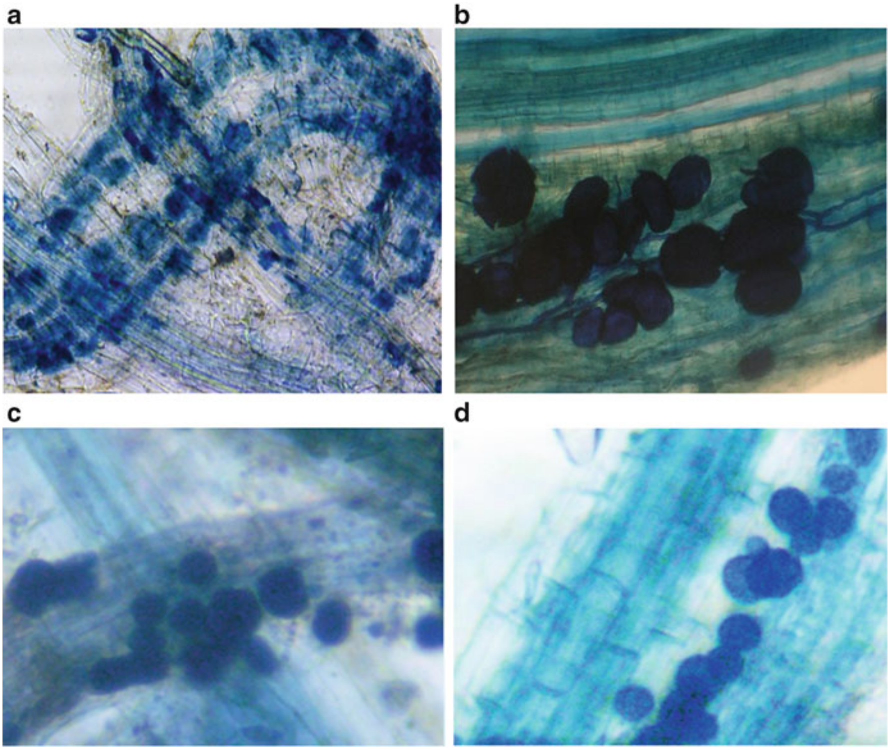

Fig. 16.7 Arbuscular mycorrhizal root colonization of *Sporobolus marginatus* growing on highly sodic soil (A) presence of arbuscules in the cortical cells, (B) presence of round and globose vesicles with attached hyphae, and (C-D) presence of Arbuscular mycorrhizal fungal root colonization in roots of *Panicum miliare* growing on saline water-irrigated soil (From Jangra 2010; Kumari 2008)

In the agrihorticulture system, the AM fungal root colonization of *Hordeum vulgare* was 83.8%. In the case of *Hordeum vulgare* and various grasses, mycorrhizal root colonization showed H and Y type of infection and presence of arbuscules and the vesicles in cortical cells.

The AM fungal root colonization was greatest in the case of *Hordeum vulgar* which has been integrated with *Carissa carandas* agrihorticulture system. The AM fungal colonization of roots in various grass species under silvopastoral system ranged from 47.8% to 71.2% (Table 16.5). AM fungi exist in two different phase: inside the root and in the soil. The intraradical mycelium consists of hyphae and other fungal structures such as arbuscules and vesicles. This phase is connected to the soil mycelium. The extracellular mycelium forms spores, exploring a new area for colonization in the soil (Rilling 2004). In small holder agroforestry systems in Ethiopia, a significant decline in AM spore densities with soil depth has been reported by Muleta et al. (2008). In a meta-analysis, it has been shown that less intensive tillage and cover cropping are viable strategies for increasing AMF root colonization for a wide range of soil types and cash crop species (Bowles et al. 2016).

Table 16.5 Spore density and arbuscular mycorrhizal (AM) root colonization in some predominant plants of silvopastoral, agrihorticulture systems and the natural grassland on calcareous soil at Hisar, in northwestern India (Based on Kumari et al. 2018)

Plant species	No. of spores per 10 g soil	Percent AM root colonization
Silvopastoral system		
Cenchrus ciliaris	175.6 ± 4.99	71.2 ± 2.65
Panicum miliare	113.2 ± 2.85	55.8 ± 1.68
Brachiaria reptans	079.2 ± 1.24	48.8 ± 1.77
Desmostachya bipinnata	066.4 ± 2.72	47.8 ± 2.74
Dichanthium annulatum	057.6 ± 1.63	55.2 ± 1.46
Agrihorticulture system		
Hordeum vulgare	203.2 ± 3.81	83.8 ± 3.51
Natural grassland		
Cenchrus ciliaris	145.62 ± 4.25	57.36 ± 3.23
Brachiaria reptans	60.4 ± 1.86	38.08 ± 2.14
Desmostachya bipinnata	42.06 ± 0.97	45.72 ± 2.05
Dichanthium annulatum	55.49 ± 1.68	50.44 ± 2.61

There is increasing evidence that AM hyphae have the ability to obtain nitrogen from decomposing litter, which can be transported to the host plant (Herman et al. 2012; Hodge and Fitter 2010; Koller et al. 2013). AM fungi possibly stimulate the decomposition of organic material, and releasing mineral nutrients, through the supply of carbon containing exudates to the decomposer microbial community (Herman et al. 2012; Nuccio et al. 2013). The hyphal exudates are composed of low-molecular-weight sugars and organic acids to high-molecular-weight polymeric compounds; these substances can both enhance and reduce bacterial growth in the soil (Toljander et al. 2007).

Phosphorus (P) is an essential macronutrient for plant growth, and its uptake from soil occurs mostly in the form of soluble phosphate anions (Schachtman et al. 1998). Several studies indicate the significance of AM fungi for growth of crop plants by regulating nutrient supply (Pellegrino and Bedini 2014). It has been shown that the AM symbiosis promotes the inflow of less mobile nutrients such as phosphorus to plant roots (Antunes et al. 2007). Koide and Kabir (2000) showed that extraradical hyphae of *Glomus intraradices* can hydrolyze organic P (i.e., phytate) to inorganic P which in turn can be taken up by plant roots readily. Some phosphate-solubilizing bacteria can interact synergistically with mycorrhizal fungi so as to facilitate phosphorus uptake by the plants (Caravaca et al. 2004; Cabello et al. 2005). Under field conditions, the abundance of phosphate-solubilizing bacteria belonging to the fluorescent pseudomonad group has been found correlated with the level of plant mycorrhizal colonization (Duponnois et al. 2011).

16.4.2.5 Decomposition of Litter

Singh and Gupta (1977) compiled studies on plant litter decomposition and soil respiration in terrestrial ecosystems. Decomposition has been discussed from the perspective of carbon pools and fluxes in the ecosystem of world by Schlesinger (1977). Decomposition is a complex and multistep process of breaking down of complex organic matter by soil organisms to release free the nutrients for renewed uptake by the plants (Swift et al. 1979). Litter decomposition rates have been studied in grassland and agroforestry systems in a seasonally dry tropical region at Kurukshetra, northern India, on moderately alkali soils (Gupta and Malik 1999). The litter bag studies have provided useful information on litter decomposition rates as influenced by climatic factors, litter quality, and soil fauna (Gupta and Malik 1999).

On a moderately alkali soil at Salimpur, northern India, the decomposition constant (regression coefficient) indicated that decomposition rates of different plant residues were in the order: *Eucalyptus* leaf (0.0059) > *Eucalyptus* + sugarcane straw (0.0044) > *Eucalyptus* + wheat straw (0.0043) > wheat straw (0.0041) > *Eucalyptus* twig (0.0040) > *Eucalyptus* root (0.0031). In *Eucalyptus tereticornis* agroforestry systems, the half-life period on the basis of decomposition models was 117, 173, 224,169, and 158 days for *Eucalyptus* leaf, twig, roots, wheat straw, and sugarcane straw, respectively (Fig. 16.8; Table 16.6). The single exponential model

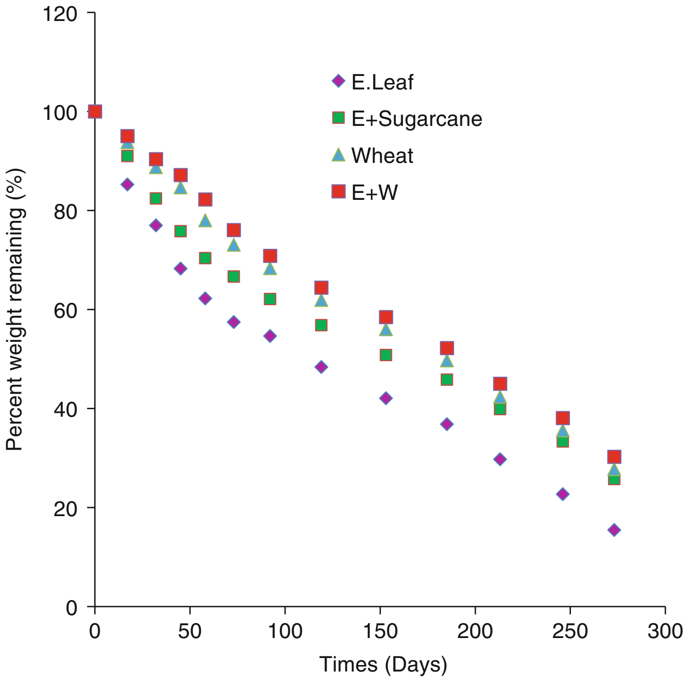

Fig. 16.8 Percent weight remaining of *Eucalyptus* leaf, wheat straw, *Eucalyptus* leaf + sugarcane straw, and *Eucalyptus* leaf+ wheat straw under *Eucalyptus tereticornis* agroforestry systems during January14, 2011 to October 15, 2011 on a moderately alkali soil at Salimpur, Kurukshetra (From Gaur 2013)

Table 16.6 Decomposition constant (k) for percent weight remaining for *Eucalyptus* leaves, wheat straw, and sugarcane straw on a moderately alkali soil at Salimpur, Kurukshetra, northern India. Half-life $t_{50} = 0.693/k$ (from Gaur 2013)

Litter type	Regression equation	Correlation (R^2)	Decomposition constant (k)	Half-life (days)
Eucalyptus. Leaf litter	$y = -0.0059x + 4.5494$	0.9713	0.0059	117
Eucalyptus. Twig litter	$y = -0.004x + 4.6264$	0.9957	0.0040	173
Eucalyptus. Fine roots	$y = -0.0031x + 4.6082$	0.9956	0.0031	224
Wheat straw	$y = -0.0043x + 4.629$	0.9849	0.0041	169
Sugarcane straw	$y = -0.0044x + 4.5622$	0.9827	0.0044	158
Eucalyptus + Wheat straw	$y = -0.0041x + 4.6434$	0.9854	0.0043	161

was found to describe the pattern of litter and straw decomposition and changes in N concentration of litter with time for *Eucalyptus tereticornis* leaf, twig and root, wheat straw, sugarcane straw, and leaf + wheat straw on a moderately alkali soil at Salimpur (Gaur 2013).

Substrate quality regulates the decomposition rates and nitrogen release from decomposing litter. The decomposition rates and nitrogen release patterns were affected by litter type, being higher for *Eucalyptus* leaf litter, and showed greater decomposition rates and nitrogen release as compared to that of wheat and sugarcane straw. The decomposition of *Eucalyptus* leaves in the months of December to March would coincide with the growth period of wheat supporting the synchrony hypothesis of nutrient release. There was synchrony of nutrient release from decomposing leaves with that of crop growth.

16.4.2.6 Carbon Sequestration

Carbon sequestration can occur in plant biomass, organic and inorganic carbon in surface soil, and carbon storage in soil profiles. In terrestrial ecosystems (i.e., soils, trees, and other vegetation), carbon sequestration is a natural process based on photosynthesis and humification of biomass (Lal 2009). Every year, ~121 Pg (Pg = petagram = 10^{15}g) of CO_2-C from the atmospheric pool is photosynthesized into plant biomass, out of which ~60 PgC is returned back to the atmosphere by plant respiration and the remainder 61.6 PgC by soil respiration. Plant biomass and soil organic matter constitute the major pool of carbon in terrestrial ecosystems. The biotic pool in vegetation stores about 610 PgC at any given time (Amundson 2001). The total amount of carbon in the world's soil organic matter is estimated to be 1500–1580 PgC (Schlesinger 1991; Amundson 2001; Lal 2004). According to the IPCC report 2007 (Smith et al. 2007), mixed-species plantings usually provide environmental benefits and public good benefits in addition to carbon sequestration. Such benefits may include biodiversity increase, salinity mitigation, pollination, carbon sequestration, and amenity value (Polglase et al. 2011, 2013; Paul et al.

2013). A substantial amount of carbon can be stored in soils and plant biomass in agroforestry systems on salt-affected soils.

16.4.2.6.1 Carbon Sequestration in Plant Biomass

The tree plantations on salt-affected soils have the potential for carbon sequestration through buildup of soil carbon as well as carbon accumulation in plant biomass (Bhojvaid and Timmer 1998, Garg 1998, Kaur et al. 2002a, b). In an age sequence of *Prosopis* plantations, trees have been found to ameliorate highly sodic conditions by moderating sodium toxicity and causing the improvement of soil fertility (Bhojvaid and Timmer 1998). These workers showed the annual rate of increase of 1.4 Mg C ha^{-1} yr^{-1} over a 30-year period in *Prosopis* plantations on highly sodic soils. Glenn et al. (1992) estimated that 0.6–1.2 gigatonnes of C per year could be assimilated annually by halophytes on saline soils; 30–50% of this carbon might enter long-term storage in soil. Thus, halophytes growing on saline soils could bring about increase in soil carbon sequestration.

In silvopastoral agroforestry systems on sodic soils at Bichhian, the total carbon storage in plant biomass was 1.18–18.55 Mg C ha^{-1}, and carbon flux in net primary production ranged from 0.98 and 6.50 Mg C ha^{-1} $year^{-1}$(Kaur et al. 2002a). In the case of 6-year-old *Prosopis juliflora* + *Desmostachya bipinnata* silvopastoral systems, bole and branches contributed 82% of the total biomass carbon in the systems (Kaur et al. 2002a). Total carbon storage was estimated to be 18.54–12.17 Mg C ha^{-1}, and carbon input in net primary production was 6.50–3.24 Mg C ha^{-1} $year^{-1}$**.**

In southwestern Australia, the rates of C sequestration in biomass of *Eucalyptus globulus* over a 10-year period were found to be substantially high that ranged from 3.3 to 11.5 t C ha^{-1} $year^{-1}$ on a large-scale watershed (Harper et al. 2005, 2007).

The underutilized species like *Elaeagnus angustifolia*, *Ulmus pumila*, and *P. euphratica* showed high potential for afforestation of the degraded cropland in the lower Amu Darya River region of Uzbekistan. After 5 years of afforestation, the soil organic C (SOC) pool increased by 10–35% by adding 2–7 Mg C ha^{-1} to the upper 0–20 cm soil layer, *E. angustifolia* being the most effective tree species in soil C sequestration (Dubovyk et al. 2012). Depending on tree species, C sequestration in woody biomass ranged from 11 to 23 Mg ha^{-1} (Dubovyk et al. 2012).

Carbon sequestration has been estimated both in plant biomass and soil in two pasture systems (*Cenchrus ciliaris* and *Cenchrus setegerus*), two tree systems (*Acacia tortilis* and *Azadirachta indica*), and four silvopastoral systems (combination of one tree and on grass) on moderately alkaline soils (soil pH 8.36–8.41) at Kachchh, Gujarat (Mangalassery et al. 2014). Carbon sequestration was maximum for the silvopastoral system of *Acacia* + *C. ciliaris* (6.82 Mg C ha^{-1}) followed by that of *Acacia* + *C. setegerus* (6.15 Mg C ha^{-1}). Carbon sequestration was 6.02 Mg C ha^{-1} in sole plantation of *Acacia tortilis.* The silvopastoral system of *Azadirachta indica* + *C. ciliaris* and *Azadirachta indica* + *C. setegerus* showed a total carbon stock of 4.91 and 4.87 Mg C ha^{-1}, respectively, whereas in sole plantation of neem, it amounted to 3.64 Mg C ha^{-1}. The soil organic carbon stock in the silvopastoral system was 36.3–60.0% higher as compared to the tree system and 27.1–70.8% higher as compared to the grass-only system. Thus, silvopastoral system can play an important role in carbon storage and improving soil conditions (Mangalassery et al. 2014).

Biomass and carbon sequestered by 5-year- and 4-month-old clonal *E. tereticornis* on waterlogged soils at Puthi, Hisar, northwest India, was 15.5 Mg ha^{-1} (Ram et al. 2011). The *Eucalyptus*-based agroforestry on waterlogged soils showed soil carbon storage of 15.823 Mg C ha^{-1}. When compared the cropland as baseline, the net carbon sequestration was found to be 4.452 Mg C ha^{-1} over a period of 4 years. Total carbon storage in *E. tereticornis* plantation ranged from 5.85 to 16.46 Mg C ha^{-1}. Carbon flux in net primary productivity of the plantation on waterlogged soils was 2.01–4.7 Mg C ha^{-1} yr^{-1} (Kumar 2012; Dagar et al. 2015b).

Plant biomass production from biosaline agroforestry in waterlogged, saline-sodic soils in India is reported to sequester 6 Mg CO_2 eqha^{-1} over the 15-year lifetime of the plantations (Wicke et al. 2013). This analysis of biosaline agroforestry indicates that the emissions from agrochemical and fossil fuel use could be compensated by carbon sequestration in belowground plant biomass and the soil.

Neumann et al. (2011) have provided estimates of carbon sequestration and biomass production rates from agroforestry in lower rainfall zones (300–650 mm) of southern Murray-Darling basin region on the basis of 121 agroforestry sites (comprised of 32 species); the average age of the plantings was 16.5 years. The various factors influencing potential productivity of the agroforestry systems included species choices, planting designs, land management practices, and climatic conditions. The average aboveground carbon sequestration rate for all measured plantations was found to be 9.5 Mg of carbon dioxide equivalents per hectare per year (CO2-e Mg ha^{-1} yr^{-1}) (Neumann et al. 2011) (Table 16.7). For different systems, the carbon sequestration rates were as follows (CO2-e Mg ha^{-1} yr^{-1}): tree-form eucalypts 10.55, mallee-form eucalypts 6.34, and non-eucalypts trees 6.92 (Table 16.7). In these lower rainfall areas, tree growth and carbon sequestration rates are naturally low, and mallee eucalypts could be the best option (Neumann et al. 2011).

Table 16.7 Aboveground dry biomass and carbon sequestration rates from trees and mallees observed in the southern Murray-Darling basin region of South Australia (based on Neumann et al. 2011)

	Rainfall (mm)	Dry biomass (Mg ha^{-1} yr^{-1})	Carbon sequestration (Mg Cha^{-1} yr^{-1})	Carbon sequestration CO2e (Mg ha^{-1} yr^{-1})
Tree eucalypts	435	5.79	2.87	10.55
Mallee eucalypts	351	3.48	1.73	6.34
Tree non-eucalypts	452	3.80	1.89	6.92
Tree-form only	437	5.58	2.77	10.15
All plants	422	5.21	2.58	9.49

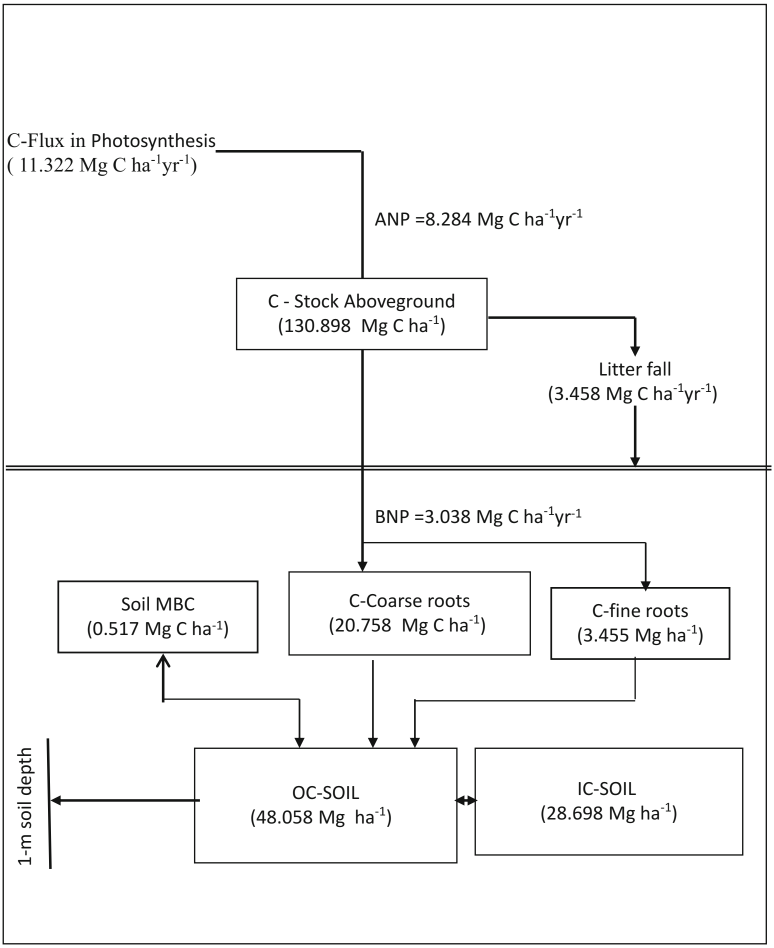

Fig. 16.9 Carbon budget of a 25-year-old *Grevillea robusta* plantation on a reclaimed sodic soil. The compartments show the carbon stock (Mg C ha^{-1}). The arrows indicate the flows (Mg C ha^{-1} yr^{-1}). (Based on Jangra et al. 2010)

In the 25-year-old *Grevillea robusta* tree plantation on reclaimed sodic soil at CSSRI, Karnal, India, the soil pH varied from 7.11 to 8.65 from 0–15 cm to 100 cm soil depth. On the basis of data on tree biomass, litter fall, fine root biomass, microbial biomass carbon, soil organic carbon, and soil inorganic carbon, the carbon pools and fluxes in the *Grevillea robusta* tree plantation showed that there was appreciable pool of carbon in aboveground biomass of trees (130.898 Mg C ha^{-1}) (Fig. 16.9). The allocation of carbon to belowground tree components amounted to 23.408 Mg C ha^{-1}. The input organic matter to the soil in litterfall was 3.458 Mg C ha^{-1}. The input carbon in fine roots amounted to 3.455 Mg C ha^{-1} assuming that fine roots have complete turnover over the annual cycle. The total

Table 16.8 Carbon sequestration rates (Mg C ha^{-1}yr^{-1}) in tree biomass, soil organic carbon (SOC up to 100 cm soil depth), and crop biomass in *Eucalyptus tereticornis* agroforestry systems on moderately alkali soil at Salimpur, Kurukshetra (From Gaur 2013)

Age (yr)	Density (trees no. ha^{-1})	Tree spacing (m)	Carbon sequestration rates (Mg C ha^{-1}yr^{-1})			
			Trees*	Crop	Total (tree + crop)	SOC
1	567	4.2 × 4.2	9.446 ± 0.436^{a}	11.387	20.836	–
2	567	4.2 × 4.2	8.204 ± 0.246^{b}	11.224	13.394	0.696
3	567	4.2 × 4.2	8.077 ± 0.324^{b}	3.772	8.530	0.518
4	567	4.2 × 4.2	7.905 ± 0.264^{b}	3.678	7.630	1.559
5	630	4.5 × 3.6	8.273 ± 0.196^{b}	3.585	7.388	1.640
6	630	4.5 × 3.6	8.459 ± 0.127^{b}	3.374	7.049	1.435
7	630	4.5 × 3.6	8.516 ± 0.139^{b}	–	8.516	4.452
8	500	5.0 × 4.0	6.752 ± 0.148^{c}	–	6.752	5.910
	LSD ($p < 0.05$)		0.746	0.500	0.860	0.242

*Values not marked with the same superscript letter (e.g. $^{a,\ c}$) are significantly different (DMRT; $p < 0.05$)

input of carbon through net primary productivity was 11.322 Mg C ha^{-1} yr^{-1} (Jangra et al. 2010). The organic and inorganic carbon pool up to 1 m soil depth was 48.058 Mg C ha^{-1} and 28.698 Mg IC ha^{-1}, respectively. The soil microbial biomass formed 1.91% of total soil organic carbon up to 30 cm soil depth (0.593 Mg C ha^{-1}).

Carbon budget of *Eucalyptus tereticornis* (clonal) agroforestry system (01–8 year old) at Salimpur, Kurukshetra, the carbon pool in trees biomass ranged from 9.446 ± 0.436 to 44.145 ± 0.879 Mg C ha^{-1} in 1- to 8-year-old agroforestry systems (Table 16.8). In the crop under *Eucalyptus tereticornis*-based agroforestry systems, the sugarcane accumulated 11.224 ± 0.305 to 11.387 ± 0.231 Mg C ha^{-1}, and wheat crop accumulated 3.772 ± 0.050 to 3.374 ± 0.093 Mg C ha^{-1} in 1- to 6-year-old agroforestry systems at Salimpur. The total carbon stored in tree+crop system ranged from 20.836 ± 0.579 to 44.145 ± 0.879 Mg C ha^{-1}. The soil organic carbon (SOC) stock up to 100cm soil depth varied from 21.317 ± 1.935 to 37.527 ± 3.834 Mg C ha^{-1}, and soil inorganic carbon (SIC) pool varied from 27.440 ± 2.161 to 43.203 ± 1.157 Mg C ha^{-1} in different *Eucalyptus tereticornis*-based agroforestry systems. Soil microbial biomass carbon was found to decrease along the depth and ranged from 0.197 ± 0.008 to 0.403 ± 0.008 g C kg^{-1} soil. Total soil carbon pool was found to increase with the age of *Eucalyptus tereticornis* and ranged from 51.054 ± 4.742 to 73.621 ± 5.352 Mg C ha^{-1}.

The carbon sequestration rate in *Eucalyptus tereticornis* trees averaged 8.204 ± 0.141 Mg C ha^{-1} yr^{-1}, whereas soil sequestered carbon at rates of 2.316 ± 0.041 Mg C ha^{-1} yr^{-1}. The average rate of total carbon sequestration (tree+crop) in *Eucalyptus*-based agroforestry systems was 10.012 ± 0.148 Mg C ha^{-1} yr^{-1}. The carbon sequestration rates in *Eucalyptus tereticornis* trees ranged from 9.446 ± 0.436 to 6.752 ± 0.148 Mg C ha^{-1} yr^{-1}. The potential of agroforestry systems to sequester carbon depends on the type of system, plant species composition, plantation age, environment factors, and management practices (Jose 2009). Studies have shown that the average annual carbon storage rate in *Eucalyptus*-based agroforestry systems was 8.61 Mg ha^{-1} yr^{-1} (Prasad et al. 2012). According to Joshi et al. (2013), the young *Eucalyptus* hybrid plantation sequestered carbon at the rate of 7.89 Mg C ha^{-1} yr^{-1}, whereas *Dalbergia sissoo* plantation stored carbon at the rate of 6.47 Mg C ha^{-1} yr^{-1}carbon.

16.4.2.6.2 Soil Carbon Sequestration

The soil organic matter is an important indicator of soil quality and the ecosystem services. Improving soil organic carbon pool is an important strategy for reclaiming salt-affected soil, which are characterized by low organic carbon. The long-term aim is to create a positive ecosystem C budget. Soil carbon is in a constant state of flux as it responds to inputs of organic matter and losses occurring through litter decomposition and mineralization by the soil microbes. Changes in soil management practices that increase organic matter inputs may drive changes in the soil carbon pool size. The capacity for soils to sequester carbon depends on the specific maximum equilibrium levels of soil organic matter that can be achieved for any farming system due to the climatic and edaphic limits on plant dry matter production and decomposition rates (Powlson et al. 2011).

Soil carbon sequestration in 0–30 cm soil layer ranged from 6.839 to 20.50 in different agroforestry systems and grassland systems of salt-affected soils (Table 16.9). In the *Prosopis juliflora* + *Desmostachya bipinnata* and *Prosopis juliflora* + *Sporobolus marginatus* silvopastoral systems on sodic soils, the soil carbon pool ranged from 13.431 to 9.621 Mg C ha^{-1} (Kaur et al. 2002a). For the saline-sodic calcareous soils, the total organic carbon for the silvopastoral systems was (Mg C ha^{-1}) 6.839 native grassland, 21.195 *Acacia nilotica*+ *Cenchrus ciliaris* silvopastoral, and 20.181 *Salvadora persica*+ native grasses system. The soil organic carbon was greater in the case of silvopastoral systems as compared to the native grassland (Table 16.9).

For the *Carissa carandas* agrihorticulture system with *Hordeum vulgare*, there was substantial buildup of organic carbon in the soil. The plants of *Carissa carandas* were planted in furrows, whereas the barley crop was grown in between the rows of *Carissa carandas* agrihorticulture system. The organic carbon at 0–15 cm soil depth varied from 78 to 93 Mg C ha^{-1}, whereas at 15–30 cm soil depth, total soil organic carbon was 62–66 Mg C ha^{-1}. In the grassland system, the organic carbon was 39 Mg C ha^{-1} and 30 Mg C ha^{-1} at 0–15 cm and 15–30 cm soil depths, respectively.

Across the Australian wheat belt, it has been estimated that more than 60% of soil organic carbon has been lost from the top 10 cm of soil, which requires management strategies for extra soil carbon sequestration (Chan et al. 2010). For managing dryland salinity and rebuilding biodiversity, the restoration of native eucalypts on degraded agricultural landscapes could be useful. Harper et al. (2012) conducted two 26-year-old reforestation experiments with four *Eucalyptus* species (*E. cladocalyx* var. *nana*, *E. occidentalis*, *E. sargentii*, and *E. wandoo*), whereas agricultural field served as control. Soil organic carbon storage (to 30 cm soil depth) ranged from 33 to 55 Mg C ha^{-1}(Harper et al. 2012). In the case of the reforested plots, there was

Table 16.9 Soil carbon sequestration at 0–30 cm soil depth in different agroforestry systems on salt-affected soils (based on Gupta and Dagar 2016)

Agroforestry System	Site	Soil Carbon sequestration (Mg C ha^{-1})	CO_2 sequestration (Mg CO_2 ha^{-1})	Reference
Prosopis juliflora + *Desmostachya Bipinnata* silvopastoral system	Sodic soils at Bichhian, north-west India	13.431	49.247	Kaur et al. (2002b)
Prosopis juliflora + *Sporobolus marginatus* silvopastoral system	-do-	9.621	35.28	Kaur et al. (2002b)
Eucalyptus plantation soil depth = 150 cm	Sodic soil of UP India	24.56–27.09	90.05–99.33	Mishra et al. (2003), Lal (2009)
Acacia nilotica + *Cenchrus ciliaris* silvopastoral system	Saline-sodic calcareous soils Hisar, India	20.50	75.17	Kumari et al. (2018)
Salvadora persica + native grasses silvopastoral system	-do-	19.48	71.43	Kumari et al. (2018)
Carissa carandas + *Hordeum vulgare* agrihorticulture system	do-	14.13–14.25	51.81–52.25	Kumari et al. (2018)
Grassland	-do-	7.06	25.89	Kumari et al. (2018)
Eucalyptus Clonal agroforestry on waterlogged soils	Puthi, Haryana state, India	15.827	58.03	Kumar (2012)
Jatropha curcas, energy plantation soil depth = 15 cm	Sodic soil, Banthra Lucknow, India	10.428–7.650	38.237–28.050	Singh et al. (2013)

additional carbon storage in the tree biomass (23–60 Mg C ha^{-1}) and ground floor litter (19–34 MgC ha^{-1}). Litter represented 29–56% of the biomass carbon; thus the protection of this litter in fire-prone, semiarid farmland could be an important component of carbon management (Harper et al. 2012).

16.4.2.6.3 Soil Organic Carbon Storage in Aggregates

Soil structure regulates to a large extent many physical, chemical, and biological properties of soil. An aggregate is a naturally occurring group of soil particles, which helps in the movement of air and water through the soil and protection of soil organic matter (Oades 1984). There are three size classes of soil aggregates, i.e., primary

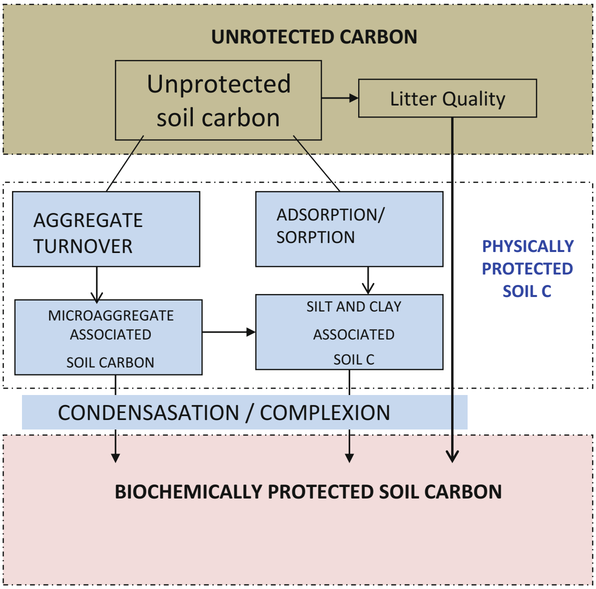

Fig. 16.10 Mechanisms of carbon protection in soil and the role of soil aggregates (Based on Six et al. 2002a, b)

particles (sand, silt, and clay), microaggregates (53–250 μm), and macroaggregates (>250 μm) (Tisdall and Oades 1982). Soil aggregate stability and soil organic matter are key indicators for soil quality and environmental sustainability in agricultural systems. The SOM contained inside these microaggregates is not easily accessed by microorganisms, and the mean residence time of SOM associated with microaggregates and the silt plus clay fraction is higher than that in macroaggregates (Six et al. 2002a, b), Fig. 16.10. Therefore, the incorporation of SOC into microaggregates and the silt plus clay fraction is a mechanism for C sequestration (Skjemstad et al. 1990). Soil physical fractionation forms a useful tool to evaluate changes in soil C and SOM dynamics. The microaggregates (250-53 μm) and silt and clay fraction (<53 μm) form a large fraction of the soil aggregates and protected most of the soil organic carbon in sodic soils. Carbon associated with microaggregates has been found as an early indicator of SOC changes associated with management practices in agricultural systems (Six and Paustian 2014).

For the silvopastoral and agrihorticulture agroforestry systems on saline water-irrigated soils, Kumari et al. (2018) found that the organic carbon stock in macroaggregates were significantly lower than in the microaggregate and silt + clay fractions (Fig. 16.11). In addition, the SOC in differently sized aggregates decreased with increasing soil depth, which is in accordance with the observed trend of SOC along with soil depth. The silvopastoral systems showed increase in the content of the water-stable aggregates as well as the increase in SOC content in the microaggregate and silt + clay fractions.

In *Acacia nilotica* and *Salvadora persica* silvopastoral system, the macroaggregates formation improved under the silvopastoral systems. In the agrihorticulture system, the microaggregates (0.250–0.053 mm) across soil depth

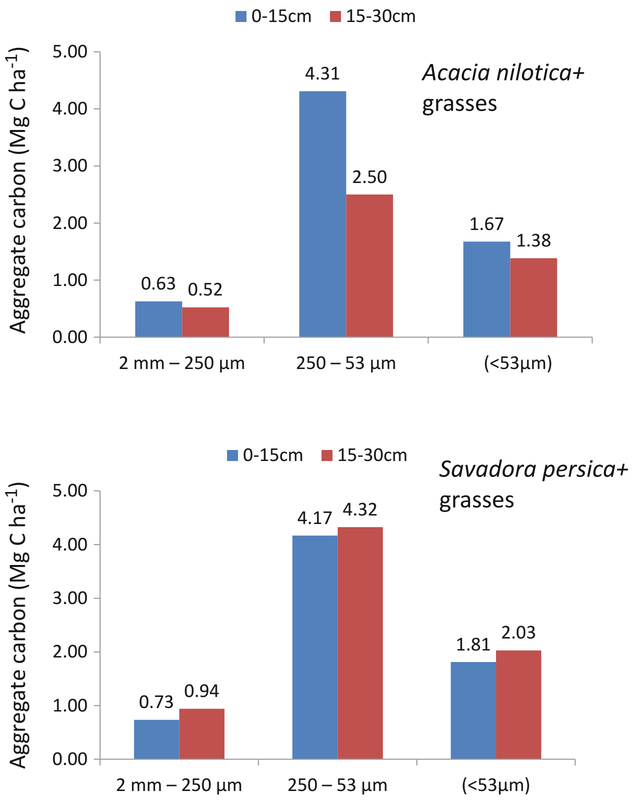

Fig. 16.11 The organic carbon stock in soil macroaggregates and the microaggregate fractions in *Acacia nilotica* and *Salvadora persica* agroforestry systems developed on calcareous soil receiving saline water irrigation (From Kumari et al. 2018)

varied from 31.18 ± 4.075 to 46.09 ± 2.737%, whereas the clay- and silt-associated fractions ranged from 35.66 ± 2.345 to 61.50 ± 3.390%. Stability of water-stable soil aggregates, as measured by geometric mean diameter (*GMD*) mm and mean weight diameter (*MWD*) mm, varied with soil depth in different agroforestry systems. *MWD* was greater at 0–7.5 cm than at the 15–30 cm soil depth. Mean weight diameter (*MWD*) mm tended to decrease with soil depth in all the systems. Geometric mean diameter (*GMD*) mm showed decrease with soil depth in most of the treatments. *GMD* decreased with an increase in the soil depth and exhibited higher values for agroforestry systems as compared to the natural grassland system. A decrease in *GMD* and *MWD* with an increase in the soil depth has been reported for conservation tillage systems by Zheng et al. (2018).

Stocks of organic carbon associated with aggregates decreased with soil depth and varied among systems and aggregate fractions.

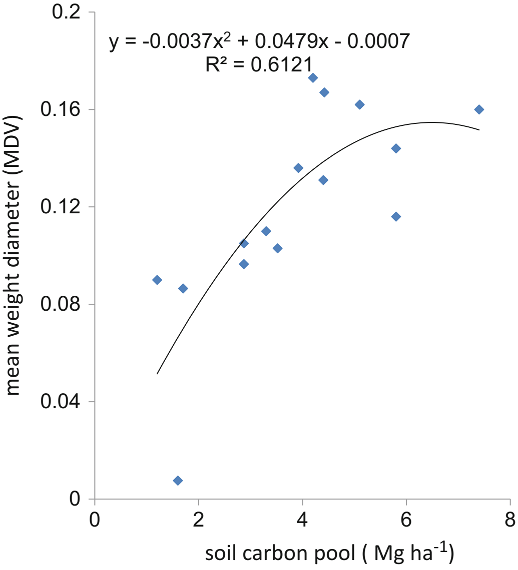

Fig. 16.12 Correlation between mean weight diameter (MDV) mm and soil carbon for different agroforestry systems on calcareous soil receiving saline water irrigation (From Kumari et al. 2018)

In addition, there was a significant correlation between SOC and mean weight diameter *(MWD)* mm (correlation coefficient = 0.782) (Fig. 16.12), suggesting that aggregate-associated C made an important contribution to SOC accumulation and soil C pool balance in the system.

16.4.2.7 Soil Inorganic Carbon Sequestration

Soil inorganic carbon and its dynamics in arid and semiarid regions are important (Lal and Kimble 2000). The soil inorganic carbon represents a large proportion of total soil carbon in Indian soils with long turnover time (Bhattacharya et al. 2008).

On reclaimed sodic soils in north-west India, the soil inorganic carbon stocks in the tree plantations of *Prosopis juliflora* and *Eucalyptus tereticornis* were (Mg IC ha^{-1}) 1.561–2.458 (30–45 cm soil depth), 4.242–5.252 (45–60 cm soil depth), and 18.596–16.901 (60–100 cm soil depth) (Jangra 2010). This shows that soil inorganic carbon (SIC) increased substantially with increasing soil depth. Studies have indicated that the soil inorganic carbon pool can improve soil physical properties as well as enhance total carbon sequestration in the soils (Pal et al. 2000; Bhattacharya et al. 2004). In the southern Gurbantunggut Desert of China, the deep soil layer contained considerable inorganic carbon, with more than 80% of the soil carbon stored below 1 m soil depth, in the form of SDIC or SIC, which could be significant in soil carbon sequestration (Wang et al. 2013).

Healthy soil provides a wide range of ecosystem goods and services that play a crucial role in sustaining biological productivity on marginal lands. There was a large potential for carbon sequestration in 25-year-old *Grevillea robusta* tree plantations on reclaimed sodic soil at CSSRI, Karnal, amounting to 157.257 Mg C ha^{-1}. Soil inorganic carbon (SIC) at soil depth greater than 45 cm provided greater potential for carbon sequestration. The inorganic carbon is present mostly in the form of $CaCO_3$ in the soils of the study area (Bhumbla et al. 1970). In contrast to soil organic carbon distribution spatially, most of soil inorganic carbon was found concentrated at 60–100 cm soil depth. The dissolution of preexisting carbonates in the upper soil layer may get translocated vertically causing its precipitation in the subsoil. Formation of soluble calcium bicarbonates helps in restoring soluble and exchangeable calcium levels in the soils as well as improving soil physical properties by decreasing exchangeable sodium percentage (Sahrawat 2003; Bhattacharyya et al. 2004). Thus, inorganic carbon provides a mechanism for carbon transfer between organic and inorganic form for carbon sequestration and maintaining soil quality (Sahrawat 2003; Bhattacharyya et al. 2004).

16.4.3 Climate Change Mitigation and Adaptation

In recent times, atmospheric concentration of carbon dioxide has increased from pre-industrial levels of 280 ppm to about 406.67 ppm on 25 August 2018 indicating a pronounced human impact on terrestrial and marine ecosystems (IPCC 2014). Averaged over all land and ocean surfaces, temperatures have warmed 0.85 °C (0.65–1.06 °C) over the period 1880 to 2012 (IPCC 2014). The pre-industrial level of carbon dioxide was 280 ppm, whereas safe limit of CO_2 levels in the atmosphere is 350 ppm.

The various cost-efficient climate change mitigation measures include reduced fossil fuel use, enhancing resource-use efficiency, reduced nitrogen fertilizer application, increasing plant productivity, substitution of wood based products to energy and energy-intensive materials, carbon sequestration in plant biomass and soil, and creating positive carbon budget. Agroforestry can add a high level of diversity on degraded lands with an accompanied increased capacity for supporting numerous ecological and production services that impart resiliency to climate change impacts (Verchot et al. 2007; Schoeneberger et al. 2012). The mixing of woody plants into crop, forage, and livestock operations provides greater resilience to the interannual variability through crop diversification as well as through increased resource-use efficiency (Olson et al. 2000). Climate change adaptation refers to the use of a global change scenario to estimate the impact of global change on the system of interest and then undertake such strategies that adapt the system to these. For example, farmers can vary the planting date or switch to different crop types or develop new crop types (Steffen, et al. 2004). Ecosystems through more structural diversity, functional diversity, and diversified production can contribute to adaptation because of multiple links between ecosystem services and climate change (Locatelli 2016).

The potential for agroforestry for carbon sequestration and dryland salinity reduction has been analyzed for low rainfall (330 mm/year) and medium rainfall (550 mm/year) salinity-impacted regions in Western Australia for the purpose of selling carbon credits, from a landholder's perspective (Flugge and Abadi 2006). The analysis used a whole-farm optimization model to determine the viability of carbon sequestration activities. Trees used for carbon sequestration in both models were assumed to be *Eucalyptus* species that are suited to medium to low rainfall regions in Western Australia. This study indicated that the price of carbon need to be higher (A$25-A$46/tCO2-e) than expected (A $15/tCO2-e) so as to make growing trees an attractive investment for landholders in regions under high and low rainfall areas. The carbon sequestration activities can only be adopted by land owners if the carbon price and salinity prevention benefits are taken into consideration (Flugge and Abadi 2006). Western Australian research has also shown that competition for water and nutrients between mallee trees and crops is a significant cost to farmers and needs to be considered while designing integrated mallee agroforestry systems (Sudmeyer et al. 2012). The emerging carbon market may provide a new agroforestry option for landholders through carbon sequestration.

There are large variation in carbon sequestration rates for salt-affected soils, which is primarily explained by differences in the soil type, initial soil conditions, climate, and differing litter production rates of the tree species (Wicke et al. 2013). Biosaline (agro) forestry systems may potentially have the positive effect of improving water infiltration and soil moisture retention. It is interesting to note that including trees in the agricultural production system can help remove excess water, thereby reducing waterlogging. Various studies have shown that if properly implemented, the biodrainage systems can lower groundwater tables (see Wicke et al. 2013; Dagar et al. 2016b).

16.5 Conclusion

One of the main challenges faced by farmers for utilizing salt-affected lands is initial high cost and delayed economic returns from agroforestry systems. Many of the ecosystem services of agroforestry have not yet been analyzed or neglected in most of studies. The farmers and land managers are not familiar with the range of ecosystem services provided by agroforestry systems; as a result the perceived value of agroforestry is low. Thus, the economic instruments based on ecosystem services need to be developed for greater adoptability of agroforestry for sustainable utilization of salt-affected lands and providing livelihood opportunities to the local people.

The service functions of the agroforestry systems such as biodiversity, carbon sequestration, pollination, water quality, salinity control, biomass production, and soil conservation are gaining the attention of researchers, planners, and politicians. Thus, productivity-integrated tools along with ecosystem functioning and services are needed to ensure sustainable agroforestry in saline environments. Improving soil productivity of salt-affected soils is critical to formulate management strategies so as to meet increasing demands of food, fodder, biomass energy, and industrial products for human society. Agroforestry systems can reduce risks under climate change by creating more diversified systems with diversified products. The complexity and diversity of agroforestry systems has the potential for meeting greenhouse gas objectives as well as providing the resilience for attaining the ecosystem service goals on a long-term basis.

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Part IV

Management Opportunities and Strategies

Identification, Evaluation, and Domestication of Alternative Crops for Saline Environments

17

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Abstract

Increased population pressure, climate change impacts, degradation of productive agricultural lands, and scarcity and poor-quality of water have significantly increased the gap between potential and actual crop yields, especially in developing countries. Salinity and associated problems like sodicity, waterlogging, and droughts reportedly lead to about 2000 ha of land to produce lesser amount of crop productivity per day. In order to meet the future food security challenges, not only the physical resources, including marginal lands and poor-quality waters, need to be managed and used more efficiently, but also new and alternative crops that could produce economic yields under the harsh climatic conditions have to be identified and introduced to sustain agricultural production.

Though conventional breeding, biotechnology and genetic engineering technologies have contributed to increased crop tolerance levels to abiotic stresses in glycophytes, that still will not increase production by 50% to meet the food demands by 2050. It will be imperative to look for neglected and underutilized crops to meet the demand for food, fuel and fiber. In order to introduce and adapt new crops, it is necessary that they are evaluated both at small and large scale to assess them from a sustainability perspective and the whole value chain worked out for their environmental and economic feasibility.

This review describes the full potential of some of the underutilized crops and species under changing climate scenarios and adaptability to marginal

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environments, especially saline areas. A number of candidate crops, including vegetables, field crops and forages studied for both short- and longer-term productivity under different salinity environments, are described. The paper also discusses the future potential and the R&D directions needed to scale out these crops for commercial purposes.

Keywords
Salinity · Marginal environments · Crop production · New and alternative crops · Underutilized species · Halophytes · Forages · Model farms · Agroforestry · Biosaline agriculture

17.1 Introduction

There is sufficient evidence that the availability of productive agricultural land per capita is declining in many developing countries, even as projections for world population growth over the next 20 years clearly show that there is need to increase food production by 50% or more (Fischer et al. 2014). Further, the agricultural productivity is sensitive to environmental stresses, especially salinity, temperature extremes, and water scarcity. Additionally, climate change and projections of climate change indicate that the area suitable for agriculture, the length of growing seasons, and the yield potential along the margins of semiarid and arid areas might decrease, potentially exacerbating food insecurity (Boko et al. 2007; Godfray et al. 2010; Fischer et al. 2014).

As argued by Lotze-Campen (2011) and Thornton and Ceamer (2012), the threat of climate change has made it more difficult to enhance agricultural productivity. Climate change, alongside factors like land degradation and habitat loss, is further expected to significantly impact biodiversity in the twenty-first century (Dawson et al. 2011). Therefore, new strategies are required to overcome this major challenge for agricultural production systems. The urgent need for development of farming systems and crop varieties (Lobell and Gourdji 2012) that will be productive despite climate variability or change requires that we explore new approaches to crop breeding. This means looking both from mitigation and adaptation strategies that could sustain agricultural production (Barghouti et al. 2012; Verner 2012). Hence, to sustain agricultural productivity in stressed environments, one possible strategy is to look for new and alternative crops with trait values that currently exceed the equivalent in major crops, especially where these are evident under hostile environments such as salinity, drought, and/or heat stress restricting productivity (Mayes et al. 2011; Dagar 2018). These “alternative” crops include a wide variety of plant species naturally found under xeric and halo-xeric conditions, many of them classified as “under-explored” species and having high potential to mitigate food security threats (Dagar 2018; Rao et al. 2017; Dakheel et al. 2014; Taha and Ismail 2010; Ismail and Taha 2009; Ismail et al. 2007; Dagar et al. 2006).

17.2 Food Security and Crop Production: Now and in the Future

The United Nations in its report has projected that the global population will increase from 7.3 billion in 2015 to 9.7 billion in 2050 (http://www.un.org/en/development/desa/news/population/2015-report.html). This means that the world will require to produce double food by 2050 and, most importantly, with minimal impacts on the environment, hence sustainable intensification of agriculture that both increases yields and reduces the harmful side effects of tilling and fertilizing. Parallel with the human population growth, the livestock numbers are also expected to double by the same period, i.e., 2050; hence along with food, more feed and forage will be needed from the same piece of land. Currently many regions of the world are facing the issue of food security, as there is big gap between food production and food availability. While some countries are not only sufficient in agricultural production but also have surplus foods, others – especially the least developed – are not only facing the problem of food scarcity but also inability of purchasing food from global markets. There are also issues of food quality (mainly from nutritional perspective), making it imperative for research to also focus on nutritional quality rather than crop yield alone.

17.3 Salinity and Its Impact on Crop Production

Among the various factors that contribute to land degradation and losses, soil salinity causes major economic and environmental costs. Global annual cost of salt-induced land degradation in irrigated areas is reported to be US$ 27.3 billion because of loss in crop production (Qadir et al. 2014). Earlier, Ghassemi et al. (1995) reported that the global income loss due to salinity was about US$ 11.4 billion per year in irrigated and US$ 1.2 billion per year in non-irrigated areas. The total soil area degraded by human-induced salinization (because of poor soil and water management) is reported to be 76.3 Mha, with Africa accounting for nearly 5.9 Mha of this total (Squires and Glenn 2004). The values differ in different publications owing to how salinity is defined and how they are measured and extrapolated, but the fact remains that salinity is increasing rapidly.

In order to meet the future food demands, it will become imperative to enlarge the focus from the existing 30 or so major crops to a wider range of crops that would have higher resilience to grow under extreme climatic, land, and water scarcity conditions. This not only means introduction and adaptation of new crops but to look at alternate crop production systems and the whole value chain. Significantly, large-scale scaling-out and commercial viability will depend on both primary crop products and other secondary products to make it sustainable.

17.4 Current Production Systems and Its Limitations

In arid and semiarid areas, particularly in Indo-Gangetic plains, due to the overexploitation of groundwater for irrigation, particularly where aquifer is of good-quality, the groundwater table has depleted to a greater extent. Further, in many coastal areas, seawater intrusion has taken place where the water table was below sea level. Moreover, the growing urban areas are also taking priority over the scarce fresh water resources for their developmental works and drinking purposes leaving agriculture to use low-quality brackish and salty waters with adverse effects on productivity as most of the commonly cultivated crops are salt-sensitive (Dagar and Minhas 2016). At present, wheat, rice, and maize are the three most important staple food crops of the world. While rice (*Oryza sativa*) and maize (*Zea mays*) are salt-sensitive crops, wheat (*Triticum aestivum*) is moderately sensitive. Under field conditions, where the salinity rises to 100 mM NaCl (about 10 dS m^{-1}), rice will die before maturity, while wheat will produce about 75% less yield. Rice, however, tolerates high sodicity. Among other cereals, even barley (*Hordeum vulgare*), considered as most tolerant, dies after extended periods at salt concentrations higher than 250 mM NaCl or equivalent of 50% seawater (see Munns et al. 2006).

In dry regions, due to lack of availability of good-quality water for irrigation, most of the lands remain barren. The rehabilitation of these lands is mainly limited to two possibilities: (i) identification of suitable native plants for their domestication as food crops and (ii) devising efficient cropping systems and techniques for using limited saline groundwater resources judiciously (Dagar and Minhas 2016). Based on salinity limits of irrigation waters for arable crops as studied widely, Yadav and Dagar (2016) listed two dozens of crops, which could be cultivated in different regions of India. These studies indicate that climate, soil, and cultivars have impact on yield potential of the same crop. Further, many studies (NAS 1990; Alsharhan et al. 2003; Dagar et al. 2008, 2016a; Dagar 2014; Rao and Shahid 2014; Rao et al. 2016; DeHaan et al. 2016; Dagar and Minhas 2016) have been reported which indicate that many under-explored species can be explored for better economic returns when domesticated on saline soils or irrigated with saline water. Therefore, introduction, evaluation, and selection of suitable alternative crops tolerant to saline and marginal conditions is an important option for future agriculture in vulnerable regions.

17.5 Alternative Crops and Their Potential for Future Food Security in Saline Environments

As discussed above, in most of the dry ecologies, the use of saline or poor-quality waters for irrigation of traditional crops has deteriorated the land resources. In these areas, diversification of production systems based on salt-tolerant alternative crops will be an important strategy to sustain agricultural productivity and economic growth at the farm level. Salt-tolerant alternative crops have significant potential to sustain farm productivity by providing farmers with new cropping options for diversification of agricultural production systems, when growing traditional crops becomes uneconomical due to increased soil and water salinity (Rao et al. 2014). In fact, in recent times (Dagar and Minhas 2016; Dagar et al. 2016a, b, c), growing alternative crops is widely recognized as a potential farm-level adaptation strategy to secure food and nutritional security in fragile and changing environments. The aim of this paper is to review some of the important alternative crops/species which can be very important resources for food, nutrition, as well as income security and income generation, especially for the smallholder farmers in salt-affected environments. They vary from currently classified as "moderately salt-sensitive" to "more salt-tolerant" crops as well as some underutilized plant species such as halophytes. During the last 20 years, many national and international centers have extensively studied several such new crops for food, fuel and fiber. Though many candidate crops or species have been identified, not all are covered in this chapter. The following sections give an overview of the work done on both new and alternative crops that include vegetables, field crops, and forages, especially those with the potential to sustain productivity of salt-affected lands.

17.5.1 Major Crops

17.5.1.1 Vegetables

Vegetables not only provide nutritive food but also much higher income per hectare than staple crops. In recent times, worldwide, the production of vegetables has doubled over the past quarter century, and the value of global trade in vegetables now exceeds that of cereals (de la Peña and Hughes 2007). But, the increase in salinity of soil and water in many agricultural areas is threatening vegetable production as most of the vegetables are sensitive to salinity. Increasing demand for water from expanding populations is also constraining fresh water supplies, forcing farmers to use brackish and other low-quality waters to grow vegetables. Therefore, we would have to give more research input to find out suitable germplasm to improve the vegetable-yielding species for their salt tolerance. The salt tolerance of vegetables is also important because of their high cash value. Most vegetables are particularly sensitive to salinity throughout the ontogeny of the plant.

The salinity threshold (EC_t) of the majority of vegetable crops is reported to be low (ranging from 1 to 2.5 dS m^{-1} in saturated soil extracts), and yield decreases drastically when saline water is used for irrigation (Machado and Serralheiro 2017). However, salinity has not received much attention, in comparison with other abiotic stresses. In addition to salinity, vegetables are known to be sensitive to temperature extremes. Climate change predictions projects 1–2 °C increase in temperatures by 2030–2050 for most agricultural zones. Higher rates of evaporation due to increased temperatures are expected to aggravate land and water resources degradation with adverse effects on vegetable production. Thus, the identification of germplasm which could produce economic yields under the harsh climatic conditions will be crucial to sustain vegetable production. In recent times germplasm tolerant of high temperatures, flooding and drought has been identified, and advanced breeding lines are being developed in major vegetable crops by some researchers (de la Peña and Hughes 2007; Keating et al. 2010). A few vegetable crops most tolerant to salinity, therefore, of potential for salt-affected areas, are described below:

17.5.1.1.1 Cowpea (*Vigna unguiculata*)

Cowpea is a grain legume native from Africa and a primary source of protein for millions of people in sub-Saharan Africa and other parts of the developing world. Important characteristics of this crop include its nitrogen-fixing ability and greater drought and heat tolerance as compared to many other legumes. Cowpea has moderate tolerance to salinity – greater than corn but less than wheat, barley, sugar beet, or cotton (Hall and Frate 1996). From a research perspective, despite its resilience to stress, studies on salt tolerance in cowpea are relatively meager. In a 2-year field plot study conducted to determine the responses of both the vegetative and dry seed yield of cowpea to a range of soil salinities, Wests and Francois (1982) found that vegetative yield decreased more by increasing soil salinity than was dry seed yield. Vegetative growth was reduced 9.0% for each unit increase in electrical conductivity of the soil saturation extract beyond a threshold value of 1.6 dS m^{-1}. Dry seed yield was reduced 12% for each unit increase beyond 4.9 dS m^{-1}. Fewer pods per plant accounted for nearly all of the seed yield reduction associated with increasing salinity levels. Recently, Ravelombola et al. (2018) identified SNP markers associated with salt tolerance in cowpea, which could be used as a tool to select salt-tolerant lines for breeding improved cowpea tolerance to salinity.

17.5.1.1.2 Mustard Greens

Mustard (*Brassica oleracea*, *B. juncea*) is a winter crop cultivated for its oilseed production and also tender green leaves and stems used as a vegetable. The salt tolerance of mustard has been reported by numerous investigators (Shannon and Grieve 1999; Dagar et al. 2016a, b, c; Sharma et al. 2016). Leaf mustard is moderately tolerant to salinity, with a threshold value similar to Swiss chard (*Beta vulgaris* subsp *vulgaris*) and spinach. With late salinization, 50% reduction in yield was reported at 15 dS m^{-1}. Early salinity, however, effectively reduced the C_{50} point to about 10 dS m^{-1} (Shannon et al. 2000). In field trials at the Dubai-based International Center for Biosaline Agriculture (ICBA), the average green biomass of six accessions (selected for leafiness from a collection of 100 accessions) was found to be 3.0 g m^{-2} at 5 dS m^{-1}, which decreased to 2.8 kg m^2 (i.e., by 33%) and to 1.5 kg m^2 (i.e., by 50%) with an increase in salinity to 10 dS m^{-1} and 15 dS m^{-1}, respectively (Rao et al. 2016). The water requirement under the UAE conditions was estimated to be around 250 mm, which is very similar to lettuce and spinach, but leaf mustard has the advantage of being more salt-tolerant than these commonly grown leafy greens and hence of great potential for saline regions. Dagar et al. (2015) cultivated mustard (var. CSR 54 and CSR 56) along with fruit trees irrigating with saline water of EC 8.5 dS m^{-1} successfully.

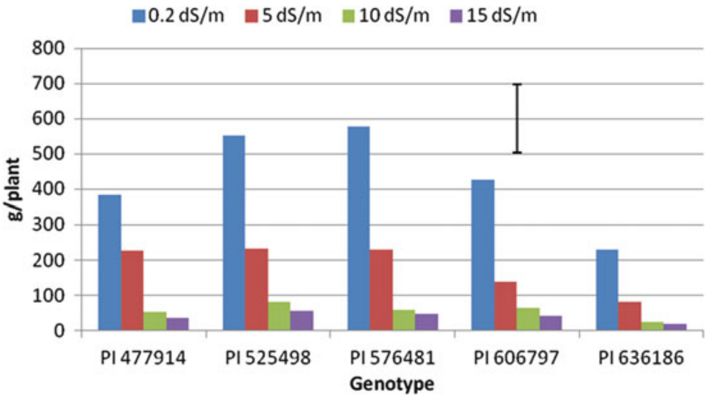

Fig. 17.1 Effect of salinity on green biomass production in five amaranth genotypes. The error bar represents the least significant difference (LSD at $p \leq 0.05$). (Source: Rao and Shahid 2014)

17.5.1.1.3 Amaranth

Amaranth (*Amaranthus* spp.) is an ancient food of the Aztecs and Mayans of Central America and is now grown in many temperate and tropical regions. All parts of the amaranth plant are edible. In Southeast Asia and Africa, amaranth is grown as a leafy vegetable, while in India and the Americas, it is most often grown for its seeds. Amaranth is fast-growing and adapted to a wide range of soils and climates. It is also one of the few C_4 crop species other than the grasses. Thus, it performs well under adverse conditions, especially heat and drought. Amaranth is reported to be moderately salt-tolerant and compares well with other vegetable crops such as cowpea and mustard (Omami et al. 2006). Recent studies in the UAE involving five genotypes showed that salinity stress significantly affects growth (Rao and Shahid 2014). Increase in salinity from 0.2 dS m^{-1} (control) to 5 dS m^{-1}, decreased plant height by 26%, stem thickness by 18%, number of branches by 28%, fresh biomass yield by 58%, and seed yield by 79%. Further increase in salinity to 10 dS m^{-1} decreased plant height by as much as 52%, stem thickness by 46%, number of branches by 37%, fresh biomass yield by 87%, and seed yield by 88%, compared to the control (Figs. 17.1 and 17.2). The study revealed that salt stress has more detrimental effect on amaranthus seed yield than on the biomass yield.

17.5.1.1.4 Cluster Bean/Guar

Guar (*Cyamopsis tetragonoloba*), also known as cluster bean, is a leguminous crop grown in Asia as a vegetable for human consumption, as forage for cattle, and as a green manure. Francois et al. (1990) reported that cluster bean is more salt-tolerant than many other grain legumes, with a high-salinity threshold of 8 dS m^{-1}. Cluster bean is also known for its drought tolerance and grows without irrigation even in areas with as little as 250 mm of annual rainfall (Undersander et al. 1991). In a field trial conducted in sandy soils at ICBA using low-salinity water for irrigation (1–2 dS m^{-1}), the mean number of pods per plant of ten accessions varied from

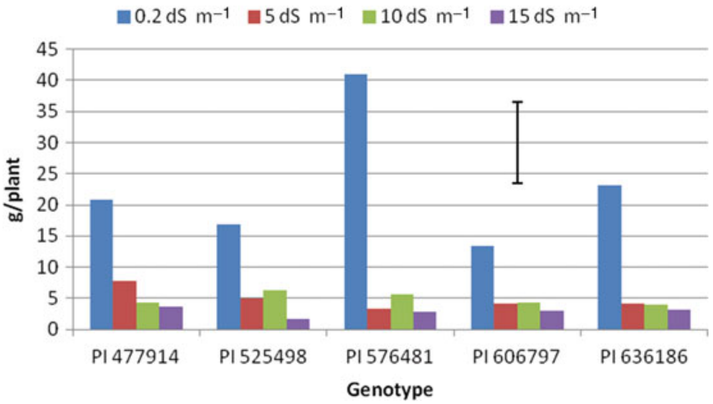

Fig. 17.2 Effect of salinity on seed yield of five amaranth genotypes. The error bar represents the least significant difference (LSD at $p \leq 0.05$). (Source: Rao and Shahid 2014)

164.4 to 113.4, with a mean of 149.4, amounting to about 12 Mg ha^{-1}. Seed yield varied between 2.5 Mg ha^{-1} and 1.4 Mg ha^{-1} with a mean of 2.2 Mg ha^{-1} over accessions (Rao and Shahid 2011a). Both pod and seed yields obtained in the UAE were higher than the average yields reported from the traditional growing areas, indicating its potential as a multi-purpose crop for the Middle East region. Water requirement for guar in the UAE was estimated to be 354 mm, similar to other vegetables such as cucumber and cabbage.

Results from the study on the effect of salinity showed significant effect on growth and yield. Compared to the control (EC_w ~2 dS m^{-1}), the mean plant height declined by 12% at 5 dS m^{-1} and 57% at 10 dS m^{-1}. Similarly, increase in salinity to 5 dS m^{-1} and 10 dS m^{-1} reduced the mean number of pods per plant by 41% and 58% of the control, respectively. Seed yield per plant was 15% less at 5 dS m^{-1} and 24% at 10 dS m^{-1}, in comparison with the control treatment (Rao and Shahid 2016). Results from these studies did not conform previous report of high-salinity tolerance of guar. Since the trial was conducted during summer under desert conditions, the combination of salinity and heat stress would have probably contributed to significant reductions in yields even at the low salinity (5 dS m^{-1}). Based on many years of study on sandy loam soil in semiarid regions of India, Dagar et al. (2015) reported average seed yield of 1.14 to 1.47 Mg ha^{-1}, when grown with three fruit trees (*Aegle marmelos*, *Carissa carandas*, and *Emblica officinalis*) as intercrop irrigating with saline water of EC_{iw} up to 10 dS m^{-1} (Fig. 17.3). Besides genotypic variation in salinity tolerance, it is also possible that the number of accessions evaluated is too small to identify genotypes with significantly high levels of stress tolerance.

17.5.1.1.5 Asparagus

Asparagus (*Asparagus officinalis*) has been considered to be the most salt-tolerant among many vegetable crops (Shannon and Grieve 1999). It can be seen growing wild among bushes on sodic as well as saline soils, particularly in dry regions. In the first year after establishment, Francois (1987) found that spear yield was reduced by

Fig. 17.3 Cluster bean with fruit tree *Emblica officinalis*, cultivated with saline water in semiarid region of India. (Source: JC Dagar)

only 2% per unit increase in soil salinity (EC_e) above a threshold of 4.1 dS m^{-1}. Asparagus is grown in many sub-tropical and temperate parts of the world but commercially important in France, Mexico, Peru, Spain, and the USA. Rao and Shahid (2011b) evaluated the performance of ten asparagus genotypes under the desert conditions using low-salinity irrigation water (2 dS m^{-1}) at the Arabian peninsula. The number of spears harvested per plant in the second year varied between 5.0 and 26.4 and the spear yield between 36.3 and 159.2 g $plant^{-1}$at 15 dS m^{-1}. In many cultivars, the spear yields obtained were comparable to the yields reported from the productive environments in the tropics, indicating that asparagus has considerable potential for cultivation under the desert conditions. Field trials involving different levels of irrigation water salinity (5, 10, and 15 dS m^{-1}) revealed that germination and growth were adversely affected at higher water salinities. At 5 dS m^{-1}, major differences were observed among the genotypes, with PI 277824 and PI 398180 being more tolerant compared to others (unpublished).

17.5.1.2 Field Crops

Over the past few years, a large number of genotypes of fast-growing, salt-tolerant, alternative dual-purpose (forage and grain or seed) crops such as barley, pearl millet, sorghum, fodder beet, and brassica were evaluated at salinity levels up to 15 dS m^{-1} under field conditions at ICBA research station, Dubai, and in other parts of the UAE. Nurseries containing 25–30 genotypes/varieties with high yield potential under saline conditions were assembled and distributed to several national programs along with appropriate management packages. Similarly, sets of genotypes of oilseed crops like safflower (*Carthamus tinctorius*) and canola (*Brassica napus*) were developed to distribute seeds to the selected farmers. Appropriate production and management packages were also developed that incorporate crop selection, irrigation, and soil management and crop management practices for optimum production in salt-affected environments. These genotypes showed excellent tolerance to medium- and high-salinity levels with yield decrease by 12–15% at medium salinity (10 dS m^{-1}) and about 30% at high salinity (15 dS m^{-1}). In field trials, forage yield of brassica ranged from 16.8 to 29.8 Mg ha^{-1}, fodder beet above ground yield from 2.95 to 4.26 Mg ha^{-1}, fodder beet tuber yield from 7.14 to 12.08 Mg ha^{-1}, and barley yield from 7.6 to 10.6 Mg ha^{-1} at 5 dS m^{-1} and 15 dS m^{-1}, respectively. Dakheel et al. (2015) reported the dry matter production of single-cut and multi-cut sorghum genotypes ranging between 11.1 to 31.9 and 5.4 to 7.9 Mg ha^{-1}, respectively. The dry matter production of single-cut and multi-cut pearl millet genotypes ranged between 7.1 to 30.7 Mg ha^{-1} and 21.8 to 31.7 Mg ha^{-1}, respectively. In addition to these alternative field crops, some neglected and underutilized species have also been evaluated for their productivity under harsh growing conditions. The Central Soil Salinity Research Institute in India developed two salt-tolerant varieties of mustard (*B. juncea* var. CSR 54 and CSR 56), which could yield 1.18 to 1.73 Mg ha^{-1} seeds in fruit-based agroforestry mode when irrigated with water of salinity (EC_{iw}) up to 10 dS m^{-1} (Dagar et al. 2015). Barley (*Hordeum vulgare*) was also found to be the most suitable crop for cultivation in dry areas irrigating with saline water. A grain and straw yield 2.46 and 2.95 Mg ha^{-1} was obtained when irrigated with water of EC_{iw} 10 dS m^{-1}, respectively. At the same site, pearl millet (*Pennisetum typhoides*) could produce 1.72–2.18 and 10.0 to 11.25 Mg ha^{-1} grain and straw (fodder) yield, respectively, when cultivated with different fruit tree species with lifesaving saline irrigation (Dagar 2014).

17.5.1.3 Neglected and Underutilized Crops/Species

There are many plant species with significant food and/or industrial potential which remain neglected and underutilized due to lack of a coherent strategy for their evaluation and development. The vast numbers of those unused and underutilized species represent an enormous untapped commodity resource which can help to meet the increasing demand for food and nutrition, energy, medicines, and industrial needs. Some of these untapped resources are either partly or fully domesticated, but most remain wild and unevaluated. These include cereals, pseudo cereals, fruits and nuts, pulses, vegetables, root and tubers, oilseeds and other industrial crops and medicinal plants, forages and fodder species. Dagar (2014, 2018) has reviewed the potential of many of these crops.

With the major staple food crops such as rice, maize, and to some extent wheat being sensitive to salinity, some key resources to meet the challenge to improve agricultural production are the neglected and underutilized crop/species (NUCS). In general, NUCS are known to be more resilient and better adapted than the staple crops to grow in marginal environments constrained by water scarcity, poor soil fertility, and other such yield-limiting factors (Padulosi et al. 2002; Dagar et al. 2008; Mayes et al. 2011). In addition to their crucial role in food production, the multiple uses of many of the NUCS offer greater opportunities to raise income of local people through product diversification. There are several NUCS, but under the overarching goals of food security, poverty elimination, and environmental sustainability, it is important to select appropriate species on the basis of their capacity to best address such challenges. However, NUCS have largely been neglected by research, and studies are needed to improve yields and quality of produce through identification of high yielding genotypes, better cultivation, management, harvesting and post-harvesting practices, value chains, and markets. Bringing the benefits of neglected and underutilized crops to the poor in marginal environments therefore, requires further research focus on species, especially those that have the highest potential value in terms of food and nutrition security, particularly for farmers in marginal areas.

Changes in populations overtime may be similar to those occurring in current populations that are adapted to a different environment in space. Species of plants growing across diverse environments may not only demonstrate genetic variation but most importantly adaptation to the different environments encountered in different parts of their natural range. Thus, the use of new evolving genetic resources would be the answer to secure food for humans and animals in the future. A wide range of neglected and underutilized crops were examined for their yield potential under saline and arid conditions, and results of evaluation of some key crops which are perceived to be of value for biosaline agriculture are discussed below. Prominent among them are triticale, oat, safflower, quinoa, and sesbania.

17.5.1.3.1 Triticale

Triticale (× *Triticum secale*) is a hybrid cereal obtained from wheat and rye (*Secale cereale*) hybridization. It is mainly used as animal feed, but in recent years, there has been increasing interest in utilizing triticale for food production. With the objective to investigate salinity tolerance, an international collection of triticale germplasm, consisting of 801 genotypes, was grown in pots at 10 dS m^{-1} during 2006/2007 cropping season at ICBA, Dubai. Mean biomass and grain yields were recorded as 57 and 8.5 g/pot, respectively. Multivariate analyses showed that 60% of the collection was suitable for grain production. About 134 genotypes (17% of the collection) were selected for further screening at 5, 10, and 15 dS m^{-1} during 2007/2008 growing season. The results showed that the top performing genotypes produced 40 and 30% higher grain and forage yields, respectively, at 15 dS m^{-1}, compared to the average yields of the collection. The 2 seasons of pot screening allowed the selection of 36 genotypes that were further evaluated during 2008/2009 season in field plots with 3 salinity levels, 5, 10, and 15 dS m^{-1}, and 3 replications. At 15 dS m^{-1}, 22% of the genotypes exceeded target values of forage and grain yields of 5 and 2 Mg ha^{-1}, respectively (see Fraj et al. 2014).

17.5.1.3.2 Safflower

Safflower (*Carthamus tinctorius*), although mainly grown for its high-quality oil, is an annual multi-purpose crop. The tender leaves and shoots, which are rich in vitamin A, iron, phosphorus, and calcium, are used as pot herb and salad, and safflower herbage is valuable as green fodder (Rumman and Al Gailani 2013). Historically, safflower was grown for the red and yellow dyes obtained from the petals, which are excellent for dyeing silk, linen, and cotton (Oyen and Umali 2007). The introduction of cheap synthetic dyes resulted in disuse of safflower dyes, but the growing demand for vegetable dyes internationally, not only for dyeing cloth but also for food coloring, is expected to provide safflower a significant niche for exploitation.

Safflower is among the most salt-tolerant cash crops, and many genotypes could display high yield under high water irrigation salinity. Another main advantage of safflower over other agricultural crops is its drought tolerance and the ability to adapt to hot and dry climates. Safflower has an extensive root system capable of extracting subsoil water at greater depths than other crops (Oelke et al. 1992). The results from a study at ICBA showed that safflower is moderately salt-tolerant and cultivation on salt-affected land can prove beneficial to farmers (Fraj et al. 2013). With the objective to investigate salinity tolerance, an international collection of 265 safflower genotypes was evaluated in pots under 10 dS m^{-1} during 2002/2003 by Fraj et al. (2013). A total of 60 genotypes were selected, and field plot trials were conducted over 2 consecutive cropping seasons (2003/2005) using 3 irrigation water salinities corresponding to electrical conductivities of 10 and 15 dS m $^{-1}$. Averaged over salinity levels, biological and grain yields averaged, respectively, 6 and 1.9 Mg ha^{-1} and 300 flowers per meter square, respectively. Increase in salinity from 10 to 15 dS m^{-1} reduced biological yield by 50%, grain yield by 75%, and flower number by 25%. At 15 dS m^{-1}, some genotypes maintained biological and grain yields at 7 and 2 Mg ha^{-1}, respectively. Relationships between yield components showed a threshold of 300 flowers under 15 dS m^{-1}. Many genotypes displayed higher yields due to higher salinity tolerance during branching, flowering, and grain filling stages compared to the susceptible genotypes. Stability analysis using genotypic ecovalence parameter showed that 10 genotypes were adapted to high salinity and 20 genotypes were adapted to intermediate salinity. Based on yield patterns and yield stability, 13 genotypes were selected out of the collection to constitute a nursery that is representative of the original collection over the whole range of variation for salinity response (see Fraj et al. 2013).

17.5.1.3.3 Oats

Oat (*Avena sativa*) is an annual grass grown primarily for its grain. It is widely cultivated in the temperate regions of the world and is second only to rye in its ability to survive in poor soils. Although oats are used chiefly as livestock feed, some are processed for human consumption, especially as breakfast foods. Oat forage is used for livestock feeding. Field trials were conducted at ICBA during 2012–13 growing season to study the effect of salinity on the growth and yield potential of oat. There was a 29% reduction in plant height with increase in salinity from 5 to 10 dS m^{-1}. Fresh and dry weights also decreased significantly by 53% and 54%, respectively, with increase in salinity from 5 dS m^{-1} to 10 dS m^{-1}. However, increase in salinity from 10 to 15 dS b m^{-1} resulted in only a small decline in plant height (4%) and green and dry biomass yields (15 and 24%, respectively) (Fig. 17.4).

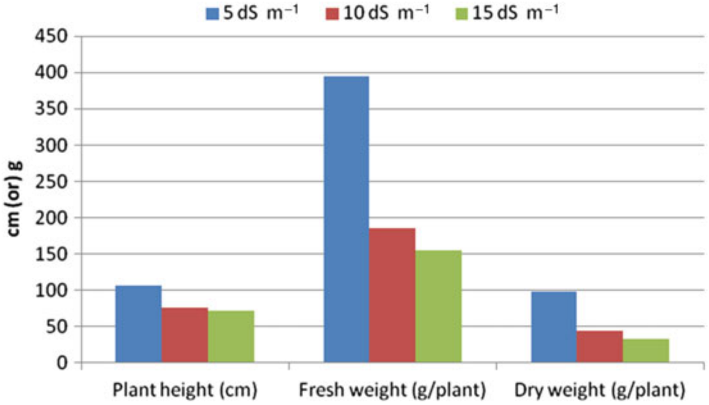

Fig. 17.4 Effect of salinity on growth and biomass yields of oat

Table 17.1 Effect of salinity on growth and biomass yields of *Sesbania aculeata*

Trait	5 dS m^{-1}	10 dS m^{-1}	15 dS m^{-1}	LSD ($p \leq 0.05$)
Plant height (cm)	261	160	122	46.7
Stem thickness (cm)	1.9	1.7	1.4	0.43
No. of branches	41	18	10	10.9
Fresh weight (g $plant^{-1}$)	697	288	142	272.8
Dry weight (g $plant^{-1}$)	194.6	63.1	29.6	65.1

17.5.1.3.4 Sesbania

Many species of *Sesbania* are short-lived perennial or annual widely distributed throughout tropical Africa and Asia. *S. cannabina/aculeata* is a tall shrub or small tree growing up to 4 m high, cultivated primarily as a green manure and source of forage for small ruminants. Sesbania is a good-quality feed, the nutritive value and dry matter digestibility being comparable to that of alfalfa, the commonly grown forage legume, and superior to most other tree and shrub legumes. ICBA studies showed that sesbania is a fast-growing legume compared to alfalfa. Water quality being similar, the dry matter yields of up to 45 Mg ha^{-1} $year^{-1}$ obtained in sesbania were considerably higher than the maximum yields of alfalfa (30 Mg ha^{-1} in 336 days) reported from the UAE (Rao 2013). In terms of salinity tolerance, sesbania also appears to be far superior to alfalfa. Sesbania reportedly tolerates salinity (ECe) of up to 8–10 dS m^{-1}, with a 40% reduction in dry matter production at 15 dS m^{-1} (Karadge and Chavan 1983), whereas the salinity threshold of alfalfa is only 2.0 dS m^{-1} (FAO 2009). In field trials conducted at ICBA, the first harvest after 6 months of growth revealed significant effect of salinity on plant height, stem thickness, number of branches, and fresh and dry weights (Table 17.1). Thus, increase in salinity from 5 to 10 dS m^{-1} has led to 39% decrease in plant height and 68% reduction in the dry weight. At 15 dS m^{-1} water salinity, plant height decreased by another 23% and dry weight by 53% (Table 17.1).

Water requirement of sesbania has been estimated to be about 580 mm, which is considerably lower than the reported demand for alfalfa which varies between

800 and 1600 mm per growing period (see FAO 2009). Another major benefit of growing sesbania would be the improvement in soil fertility due to symbiotic nitrogen fixation and the addition of huge amount of organic matter to the desert soils. Sesbania nodulated readily with the free-living rhizobia *Sinorhizobium meliloti* and *S. arboris*, native to the UAE soils (Madhumitha et al. 2014).

17.5.1.3.5 Quinoa

Quinoa (*Chenopodium quinoa*) is considered a facultative halophyte, and some varieties are able to cope with salinity levels as high as those present in seawater (i.e., EC of 40 dS m^{-1}). Salinity tolerance in quinoa greatly exceeds that of other crops considered to be salt-tolerant, such as barley. ICBA evaluated the quinoa germplasm accessions acquired from the USDA for local adaptation and yield potential during 2006–2007. Selections were made of the best performing accessions which were then evaluated for yield potential in replicated field trials using low-salinity water (EC_w 2–3 dS m^{-1}) in the following years, where yields of up to 4 Mg ha^{-1} were obtained. In subsequent field trials under highly saline conditions (EC_w 14–18 dS m^{-1}), four selected lines produced mean seed yields of up to 10 Mg ha^{-1} (Fig. 17.5) – much higher than the highest yields reported from the nonsaline traditional quinoa-growing areas (Choukr-Allah et al. 2016; Rao et al. 2016). The studies signified the importance of quinoa to rehabilitate salt-affected farms which have become uneconomical for the cultivation of the traditionally grown crops (see Toderich et al. 2013a). The green biomass yields obtained in these trials were also high indicating the potential of quinoa as an alternative forage crop for salt-affected areas.

In addition to the above-discussed crops, many species – both native and introduced – have the potential for more widespread use, and their promotion could contribute to agricultural diversification and income generation, particularly in areas where cultivation of major crops is constrained or economically unviable. Two such species that received special attention at ICBA were castor and desert gourd.

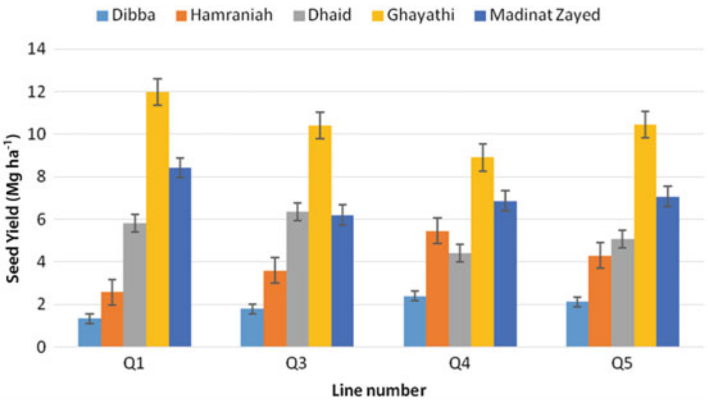

Fig. 17.5 Seed yields of four quinoa lines grown at five locations in the UAE during 2003–2014. The error bars represent LSD of the means ($p \leq 0.05$). (Source: Rao et al. 2016)

17.5.1.3.6 Castor

Castor (*Ricinus communis*) is a member of the Euphorbiaceae family cultivated on marginal lands and under rainfed conditions for seeds which contain up to 60% oil which is inedible. Castor oil has several pharmaceutical and industrial uses. Castor is also an ideal candidate for biodiesel production due to the absence of competition with food crops. Results from field trials at ICBA (Menon et al. 2014) showed that castor could tolerate salinity of up to 5 dS m^{-1} without a statistically significant decrease. In the 5 dS m^{-1} salinity treatment, the seed yields were between 1.8 and 2.3 Mg ha^{-1} for different accessions compared to the yields which ranged between 1.5 and 3 Mg ha^{-1} of seed with fresh (nonsaline) water. In comparison with the freshwater treatment, seed yield decreased by 66% and 82% with increase in salinity of up to 10 and 15 dS m^{-1}, respectively. The fact that seed yield is not significantly affected by salinity in the 5 dS m^{-1} treatment suggests that the ionic stress faced by the plant which resulted in a significant decrease in plant height is not very damaging. Within each treatment, differences between accessions for seed yield and 1000 seed weight were found to be insignificant. The results of this study suggested that castor is a suitable candidate for cultivation as a biodiesel feedstock crop in the UAE and in countries with similar climatic conditions. The yield obtained in this study upon irrigation with water of salinity 5 dS m^{-1} was on par with the global average. It could also be cultivated with success in dry regions of India applying 2–3 irrigations of saline water up to EC 8–10 dS m^{-1} (Dagar et al. 2008). This supports the possibility of cultivating castor using low-moderately saline groundwater and even recycled wastewater. Since castor is not a food crop, none of the associated food vs fuel conflicts apply to its potential as a biodiesel feedstock crop.

17.5.1.3.7 Desert Gourd

Desert gourd (*Citrullus colocynthis*) is a member of the Cucurbitaceae family. It bears inedible, potentially toxic fruits with seeds having high oil content. The plant often grows wild in sandy desert soils and on sand dunes covering large areas and surviving under hyper-arid desert conditions. Due to the growing interest in biofuels on the one hand and the concerns on using prime lands and food crops (soybean, rapeseed, etc.) for their production, desert gourd was studied for its potential as a nonedible biodiesel feedstock crop for cultivation in arid and biophysically marginal lands.

In a field trial conducted at ICBA, 27 accessions mostly collected from the UAE were assessed for their potential as a biodiesel feedstock. The seed yield ranged between 12 and 374 g per plant, while seed oil content ranged from 7.8 to 43.8% of the seed weight. The extrapolated annual oil yield in several accessions exceeded 1 Mg ha^{-1}, the highest being 3.44 Mg ha^{-1} – showing desert gourd as a highly prospective feedstock for biodiesel production using marginal lands. The oil has low viscosity, which is of great advantage in terms of potential as biodiesel feedstock (Menon et al. 2016). The oil from most accessions has a free fatty acid content less than 0.5%, which is within suitable limits for biodiesel production, though variability in saponification value suggested that the oil is prone to oxidation upon storage. The studies have also showed that it would be desirable to develop phenotypes with a more compact growth habit. Because of the viny growth habit, even though seed yield per plant is very high (up to 0.37 kg) compared to other plants studied at ICBA (e.g., castor), the per hectare yield tends to be lower. Even with this shortcoming, oil yield is higher than that of soybean, a popular biodiesel feedstock. Desert gourd has the added advantage of tolerance to extreme temperatures and marginal lands, even if it may be unsuitable for salinity-affected regions as studies showed (data not presented). It has tremendous medicinal properties in Indian traditional medicinal systems.

17.5.1.4 Halophytic Species

17.5.1.4.1 Grasses

Animal production is dependent on animal feed which until few years relied only on conventional forages. However, with climate change and nonavailability of good-quality water and productive land (mainly needed for growing crops), a sudden shift in researches has been observed worldwide to look at fodder/forage that can be grown on "marginal lands." A number of wild grasses, shrubs, and trees occurring naturally under extreme dry, saline, or other abiotic stress have been studied to look at their potential for forage and fuel (Rao et al. 2017; Dagar 2014; Ismail et al. 2007; Ismail and Taha 2009; Tomar et al. 2003; Dagar and Tomar 2002). Many workers have evaluated these resources and identified suitable salt-tolerant species (see Dagar et al. 2008, 2014, 2016a, b, c; Dagar and Minhas 2016; Dagar 2018). Among them are grasses, shrubs, and trees that yield multipotential products and can be grown on marginal lands with poor-quality water (including saline/brackish water).

A number of large-sized experiments and scaling-out trials have been made in different parts of the world to demonstrate the sustainability and quality of forage/fodder produced under extreme condition. It is imperative that such trials should be continued for at least 3–5 years to demonstrate the long-term productivity with minimal impact of possible soil salinization process, which requires intensive management practices, mainly related to irrigation and drainage.

ICBA did such long-term trials in the UAE under extreme dry weather conditions where only highly saline underground water was available for irrigation. Results from three "model farms" established in the northern region of the UAE are presented below to demonstrate that "biosaline agricultural" technologies using a combination of irrigation systems and their management with forage production systems and possible integration with the livestock and intercropping with salt-tolerant annual crops provide diversified options for income generation to the farmers in the salt-affected areas.

Four halophytic perennial forage grass species, *Distichlis spicata*, *Paspalum vaginatum*, *Sporobolus virginicus*, and *S. arabicus*, were planted in three salt-degraded and abandoned "model farms" at Mezaira'a, Madinat Zayed, and Ghayathi in the UAE. The salinity of the irrigation water in the three farms at the time of establishment of the grasses ranged between 14.1 and 17.4 dS m^{-1}. The productivity of the grasses was assessed over 3 years (2012–2014) by harvesting three times per year. Averaged over locations and species, dry biomass yields of the four grasses ranged between 32.64 and 40.68 Mg ha^{-1} year^{-1} (see Table 17.2). *Sporobolus virginicus* produced highest biomass yields, followed by *D. spicata*, *P. vaginatum*, and *S. arabicus*, although differences among the four grasses were marginal (Fig. 17.6). In Madinat Zayed and Ghayathi, the average respective forage yields in terms of water productivity were estimated to be 1.68 and 2.42 kg dry matter m^{-3} water, better than the reported yield of the traditionally cultivated Rhodes grass (*Chloris gayana*) from less saline conditions (Rao et al. 2017). The study showed that the four halophytic grasses have the potential to contribute to rationalized use of scarce water resources for forage production, besides providing options for enhancing domestic forage production through rehabilitating the salt-affected farms that are unproductive for conventional crops (Fig. 17.7).

Tomar et al. (2003) observed that forage grasses like *Panicum laevifolium* and *P. maximum* were the most suitable species under high-salinity water irrigation and produced annually 14–17 Mg ha^{-1} of dry forage showing their potential as silvo-pastoral grasses if grown in protected conditions. *Panicum antidotale*, *P. coloratum*, *P. virgatum*, *Brachiaria mutica*, *Cenchrus setigerus*, and *C. ciliaris* are among other successful grasses suitable for sandy loam soils when provided with saline irrigation. *Aeluropus lagopoides*, *Leptochloa fusca*, *B. mutica*, *Chloris gayana*, *Dichanthium annulatum*, *Bothriochloa pertusa*, and species of *Echinochloa* and *Sporobolus* were found suitable for saline vertisols and could produce good biomass when irrigated with saline water in these soils. Unlike other salt-tolerant plants, which tend to accumulate high salt content in leaves and stems, earlier studies have shown that these grasses exclude the salts at root level, hence are safe to the animals even if fed directly.

17.5.1.4.2 Shrubs

In addition to the grasses, five species of *Atriplex*, namely, *A. canescens*, *A. halimus*, *A. amnicola*, *A. nummularia*, and *A. lentiformis*, were also planted in two of the farms in the UAE (Ghayathi and Mezaira'a) (Fig. 17.8). In Ghayathi, the mean green biomass yields per year were highest for *A. amnicola* (50.9 Mg ha^{-1}) followed by *A. lentiformis* (50.6 Mg ha^{-1}) and *A. nummularia* (30.3 Mg ha^{-1}) (Table 17.3).

From the table, it can be seen that the biomass yields of the shrubs are higher in Ghayathi than at Mezaira'a. In Mezaira'a, yields were highest in *A. amnicola* (30.6 Mg ha^{-1}) and *A. nummularia* (30.3 Mg ha^{-1}), while in Ghayathi, *A. amnicola* followed by *A. lentiformis* had the highest yields (50.9 Mg ha^{-1}and 50.6 Mg ha^{-1}, respectively). Bearing in mind the quality of the irrigation water and the limited options to grow conventional crops, the reasonably good biomass yields obtained from the shrubs showed their utility for sustainable forage production in salt-degraded farms. However, as indicated by the high ash percentage, the salt content of the edible parts of *Atriplex* plants would be high when grown with saline water. Therefore, to avoid negative effects on animals in a cut and carry system, mixing

Table 17.2 The biomass yields and percentage ash content of four salt-tolerant grasses planted in three model farms in the Western Region, Abu Dhabi Emirate, UAE

Species	Fresh weight (Mg ha^{-1})	Air-dry weight (Mg ha^{-1})	Oven-dry weight (Mg ha^{-1})	Ash-free dry weight (Mg ha^{-1})	Ash weight (%)
Mezaira'a					
Distichlis spicata	29.53	10.06	8.88	2.96	13.83
Paspalum vaginatum	20.55	10.63	6.53	2.28	15.93
Sporobolus arabicus	16.52	10.00	6.83	2.36	14.37
Sporobolus virginicus	28.92	15.42	9.39	3.16	16.04
Mean	*23.88*	*11.53*	*7.91*	*2.69*	*15.04*
LSD ($p \leq 0.05$)	n.s.	4.55	n.s.	n.s.	n.s.
Madinat Zayed					
Distichlis spicata	46.42	30.63	13.67	4.88	13.95
Paspalum vaginatum	47.89	30.37	13.44	4.73	15.62
Sporobolus arabicus	43.66	30.06	13.45	4.81	14.00
Sporobolus virginicus	43.34	28.45	12.87	4.73	13.67
Mean	*45.33*	*29.88*	*13.36*	*4.79*	*14.31*
LSD ($p \leq 0.05$)	n.s.	n.s.	n.s.	n.s.	1.36
Ghayathi					
Distichlis spicata	56.54	42.23	17.66	6.21	12.17
Paspalum vaginatum	58.04	36.72	15.90	5.42	14.25
Sporobolus arabicus	48.10	27.08	12.35	4.30	13.17
Sporobolus virginicus	65.52	41.98	18.42	6.45	12.75
Mean	*57.05*	*37.00*	*16.08*	*5.60*	*13.09*
LSD ($p \leq 0.05$)	n.s.	9.85	n.s.	n.s.	n.s.

Source: Rao et al. (2017)

The data represent averages over harvests between 2011 and 2014. The number of harvests made at each location is shown in parenthesis

n.s., not significant

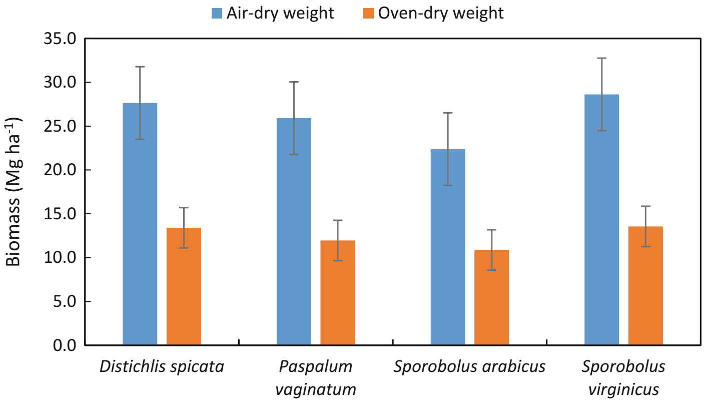

Fig. 17.6 Air-dry and dry weights of the four salt-tolerant grasses evaluated in three study farms in the Western Region, Abu Dhabi Emirate, UAE. The values represent averages over 17 harvests from 3 locations. The error bars indicate the least significant difference ($p \leq 0.05$). (Source: Rao et al. 2017)

Fig. 17.7 Halophytic grasses established on salt-affected and abandoned farms in the UAE

Fig. 17.8 *Atriplex* spp. established on a salt-affected and abandoned farm in the UAE

Table 17.3 Yields of *Atriplex* spp. (mean ± SD) from Mezaira'a and Ghayathi

Location	Species	Fresh weight (Mg ha^{-1})	Air-dry weight (Mg ha^{-1})	Oven-dry weight (Mg ha^{-1})	Ash (%)
Mezaira'a	*A. amnicola*	30.6 ± 12.6	15.3 ± 6.1	12.5 ± 4.9	NA
	A. canescens	20.8 ± 8.5	11.7 ± 4.2	9.8 ± 3.4	NA
	A. halimus	21.5 ± 7.6	12.2 ± 5.7	10.0 ± 4.8	NA
	A. lentiformis	19.4 ± 3.1	12.5 ± 2.5	10.3 ± 1.8	NA
	A. nummularia	30.3 ± 10.1	14.7 ± 5.1	12.3 ± 4.3	NA
Ghayathi	*A. amnicola*	50.9 ± 0.9	38.9 ± 2.1	27.8 ± 3.1	30.7 ± 0.1
	A. canescens	35.3 ± 3.6	30.4 ± 2.3	23.6 ± 1.8	32.4 ± 2.2
	A. halimus	46.8 ± 10.9	32.5 ± 4.6	26.0 ± 4.1	32.3 ± 0.7
	A. lentiformis	50.6 ± 9.8	36.6 ± 4.3	28.5 ± 4.5	31.6 ± 0.8
	A. nummularia	44.4 ± 1.2	31.9 ± 2.4	23.6 ± 1.3	31.2 ± 1.4

NA data not recorded

with conventional forages up to a maximum of 30% when grown under saline environments or 50–60% under non-saline conditions is usually recommended.

17.5.1.4.3 Dwarf Saltwort (*Salicornia bigelovii*)

Salicornia bigelovii, also known as dwarf saltwort, is a halophyte that grows in the coastal areas of Mexico and the USA. It is an annual plant of the family Chenopodiaceae with erect succulent stems, growing to a height of 30 cm. *Salicornia* is a delicacy salad vegetable and grown on a commercial scale for its tips in some countries (Glenn et al. 1991). The seeds contain 28% oil and 31% protein, similar in quality to soybean. Despite its potential as a crop with multiple uses, *Salicornia* improvement received very little attention. Grattan et al. (2008) showed that hyper-saline drainage water can be used to irrigate *Salicornia*. Jaradat and Shahid (2012) carried out evaluation in sandy soils with seawater irrigation and identified genotypes with favorable combinations of traits that can be used by farmers in small-scale vegetable production, in large-scale biomass and oilseed renewable bioenergy production, or for reclamation of saline lands. More recently, Lyra et al. (2016) studied several groups of traits for 11 *Salicornia* genotypes which were irrigated with full-strength seawater. Classification and ranking of the populations revealed high yielding genotypes that have good potential for seed yield improvement through breeding. The study also unveiled interesting interrelationships among growth parameters that could be used for further selection to increase seed production such as number of seeds per spike, number of branches, days to flowering, and duration of seed maturity. There is a huge potential of this species which needs extensive screening and identification of accessions/line for breeding programs to produce crops suitable for food (vegetable), fuel (seeds), and forage (residual matter). The focus needs to identify short-height and short-cycle genotypes that can mature in 5-month period to make it sustainable in dry regions.

17.5.1.4.4 Other Fodder Shrubs and Trees

Among other halophytes *Salvadora persica*, *Ziziphus nummularia*, *Kochia indica*, *Balanites roxburghii*, *Haloxylon persicum*, *H. salicornicum*, *Maireana brevifolia*, and *Feronia limonia* are prominent fodder species suitable for Indian subcontinent. These along with tree genera like *Acacia*, *Prosopis*, *Ficus*, *Ailanthus*, *Ziziphus*, *Cordia*, *Salvadora*, *Capparis*, *Melia*, *Albizia*, *Cassia*, and *Azadirachta* are traditional fodder resources of dry saline regions (Dagar 2014).

17.5.2 Agroforestry Systems

Agroforestry is a form of agriculture combining crops (including field crops and forages) with trees to optimize productivity per unit area, in addition to enriching the soil. Traditionally, it referred to the spatial integration of trees (and shrubs) with annual cropping. Agroforestry delivers some useful tree products and many claimed environmental advantages (Garrity et al. 2010; Glover et al. 2012; Gupta and Dagar 2016), but the effect on crop (or total food) yield is the key question.

Agroforestry has been practiced traditionally for a long period in Africa and India. In the western African Sahel region, up to 5 M ha of "re-greening" has taken place since ~1985 through farmer-managed natural regeneration of a variety of tree species. Classical examples include involving the leguminous tree *Faidherbia albida* with sorghum and millet grown without substantial tillage in traditional system in Niger, which result in crop yield approximately doubling compared with cropping without trees (Garrity et al. 2010); alley cropping of millet-peanut with narrow alleys of shrubs or trees in sub-Saharan Africa; and planting annual crops among the coppiced, non-leguminous, indigenous shrub, *Guiera senegalensis*, in northern Senegal. Another example is from Malawi and Zambia, where maize is planted between alleys of the leguminous species *Gliricidia*, where over 12–13 years of a continuous cropping resulted in average maize yield doubling from 1.6 Mg ha^{-1} without fertilizer to 3.2 Mg ha^{-1} with planting between coppiced *Gliricidia* alleys (Sileshi et al. 2012). Another leguminous tree *Prosopis cineraria* with all crops in dry regions of India and Pakistan is major success story.

Since agroforestry system in general increases biomass production and reduces soil degradation processes (e.g., soil erosion, dispersion, and leaching), it is likely that it also helps improve soil conditions in biosaline agricultural systems (Toderich et al. 2013b). Silvo-pastoral systems involving highly salt-tolerant trees such as *Acacia nilotica*, *A. ampliceps*, *Prosopis juliflora*, *P. alba*, *P. cineraria*, *Dalbergia sissoo*, and *Eucalyptus tereticornis* (in waterlogged situations) along with earlier-mentioned grasses are most suitable for saline environments for livelihood security of the people of the area who are mostly dependent on rearing of cattle/animals and also for reclamation of these soils. Studies have indeed reported the reduction of both salinity and sodicity under agroforestry systems on the one hand and biomass production for fuelwood, fodder, and timber on the other hand (Singh et al. 1994, 1995; Bell 1999; Dagar et al. 2001a, b; Dagar and Tomas 2002; Barrett-Lennard 2002; Qadir and Oster 2002; Singh and Dagar 2005; Ismail et al. 2007; Ismail and

Taha 2009; Fraj et al. 2013; Dagar 2014; Gupta and Dagar 2016; Yadav and Dagar 2016; Dagar and Yadav 2017). In partially reclaimed alkali soils, trees such as *Populus deltoides* and *Eucalyptus tereticornis* along with arable crops such as rice-wheat rotation or fodder crops like Egyptian clover (*Trifolium alexandrinum*) are found to be highly remunerative (Singh et al. 1995; Dagar 2014), particularly in Indo-Gangetic plains. *P. juliflora*, *Tamarix articulata*, *Acacia farnesiana*, *Parkinsonia aculeata*, *Salvadora persica*, *Eucalyptus camaldulensis*, *Casuarina obesa*, and *Acacia ampliceps* are found to be suitable trees for saline soils (Tomar et al. 1998; Dagar 2014). In waterlogged areas *Eucalyptus*, being fast growing and transpiring high amount of water, has been found to be the most promising tree to lower down the water table. For more details see Jeet-Ram et al. (2011) and Dagar et al. (2016a, b, c). On the other hand, agroforestry systems are also reported to have a risk in increasing soil salinity/sodicity, if not properly managed (Heuperman et al. 2002). Another drawback identified is the risk that salt-tolerant (tree) species may become invasive and weedy and spread into neighboring, non-salt-affected areas, especially when involving exotic species as compared to local species. However our work has shown that all exotic species may not be invasive and invasiveness actually depends on specific climatic and soil conditions.

An agroforestry system was introduced in the UAE, under very hot and dry climatic conditions, sandy dry soils, and irrigation with highly saline underground water. The main objective was to see the overall benefits, including productivity, soil improvement, nutrient efficiency, and long-term sustainability of the system. The Australian tree species *Acacia ampliceps* which was studied for the last few decades particularly in the Southeast Asian countries and reported to not only grow and sustain in salt-affected lands but proved to be highly adaptive and productive (Marcar et al. 2010) has been used. Work pioneered in Pakistan for a decade through ACIAR projects and later on carried forward by ICBA in introducing the species to many countries in Asia and Africa region has also shown its potential under harsh conditions. *A. ampliceps* was planted alternating with series plots of *Sporobolus arabicus* and *Paspalum vaginatum*, two salt-tolerant forage grasses, that have been tested extensively under saline conditions (up to 40 $dS.m^{-1}$). While some series of plots were fertilized only once during establishment and never again for 13 years, others were fertilized normally on annual basis. *A. ampliceps* proved to be a highly salt-tolerant tree species that fixed atmospheric nitrogen efficiently even under +45 °C summer temperatures and irrigation water salinity up to 30 $dS\ m^{-1}$. Analysis of the data collected over a period of 10 years showed that in presence of *A. ampliceps* trees, the green and dry biomass of the forage grasses without any fertilizer treatment showed a reduction of only ~10%, even after 10 years. In *A. ampliceps*, the total dry biomass estimated by clipping branches with leaves up to 2 m from ground surface was around 10 $Mg\ ha^{-1}$ both under fertilized and non-fertilized treatments indicating the efficient nitrogen fixing by the species (Fig. 17.9). This was also confirmed by studying the rhizobium populations in the rhizosphere of the trees. Over the 10-year period, both *S. arabicus* and *P. vaginatum* provided sustainable forage yields with the dry biomass reaching up to 25 and 15 $Mg\ ha^{-1}$, respectively, at 30 $dS\ m^{-1}$ of irrigation water salinity (Fig. 17.10).

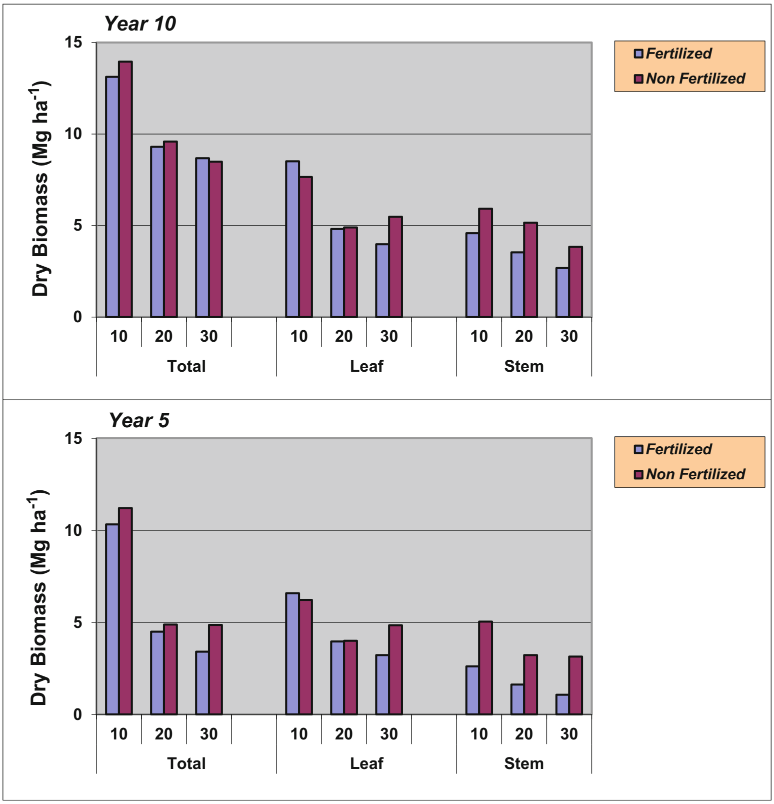

Fig. 17.9 Dry biomass of *A. ampliceps* at 5- and 10-year period when irrigated at 10, 20, and 30 dS m^{-1} of irrigation water, both with fertilizer and non-fertilizer treatments

17.6 Evaluation, Identification, Introduction, and Domestication of New Species

Identification of stress-tolerant crops and suitable germplasm is a prerequisite to broaden the resource base and increase the livelihood options especially for small holder farmers in marginal areas. This requires systematic evaluation of the new crops/ species with potential for wider use and develops those which could make a useful contribution to food security as well as non-food uses. There are major gaps in our knowledge and capacity to make the best out of the under-utilized crops because agricultural research has so far paid little attention on them. Unlike staple crop species, no processes of adaptation, improvement, and optimization of agronomic management practices have been applied to many of the under-utilized crops (Mayes et al. 2011).

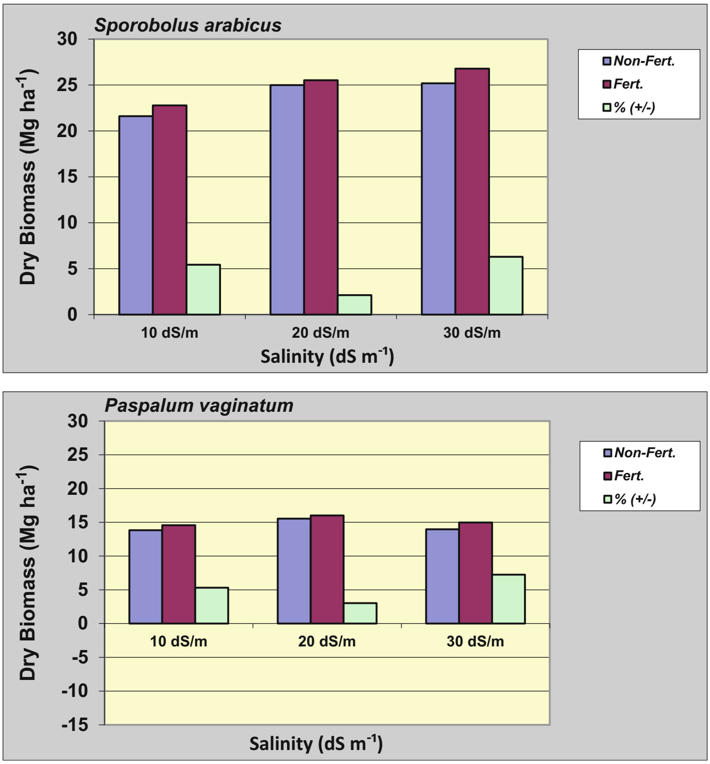

Fig. 17.10 Dry biomass of *S. arabicus* and *P. vaginatum* averaged over 10-year period when irrigated at 10, 20, and 30 dS m^{-1} of irrigation water, both with fertilizer and non-fertilizer treatments

17.6.1 Screening Procedure

In any crop, the identification of salt-tolerant germplasm with adaptation to local growing environment requires systematic screening using more than one screening method, bearing in mind that crop response to biotic stresses (salinity, heat, etc.) depends on the developmental stage and field screening is difficult when the number of accessions is large. A generalized screening procedure for seed-propagated crops/species is shown in Fig. 17.11. It integrates more than one method to be able to identify germplasm with high yield potential and good adaptation to local growing conditions, in addition to salt tolerance. If the quantity of seeds received is small, seed multiplication is conducted under open-field conditions using low-salinity irrigation water (2–3 dS m^{-1}). This facilitates simultaneous assessment of the material for general adaptation to the local environment and yield potential, which enables selection of promising accessions for further studies. Germplasm accessions (mainly annuals) which survive and produce adequate quantities of seed are subjected to mass screening at a single discriminating level of salinity under

Fig. 17.11 General concept model for screening and evaluation of new seed crops

controlled conditions in the hydroponic system (with 10-cm-diameter plastic pots filled with gravel and salt water applied in 1/4 Hoagland solution) or in soil beds under a cooled plastic tunnel/greenhouse or, alternatively, in plastic pots (20 L) filled with 1:1:1 mixture of sand, organic fertilizer, and vermiculite and buried in the ground under outdoor conditions. The system adopted for screening depends on the
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crop and number of accessions available for evaluation. Accessions that perform well go through a second cycle of screening in pots, using three levels of water salinity (low, medium, and high). Since a realistic assessment of yield is not possible with pot-screening system and the ultimate test for any crop or genotype is its ability to produce economic yields in farmer's field, the selected accessions are further assessed for their performance under field conditions in replicated trials. The field trials are repeated over 2–3 seasons to validate the results and select accessions (genotypes) that are better adapted to local growing conditions, combined with salt tolerance.

In all of the methods, seeds are germinated with fresh water, and salinity treatment is generally initiated after 2 weeks of growth, starting with low salinity and gradually increasing to the maximum over a period of 2–4 weeks, depending on the level of the treatment. In general, the parameters used to evaluate the response of genotypes include plant stand, height, days to flowering, number of branches, leaf area, number of fruits, fruit size, fruit weight, and yield.

In case of perennials, especially for halophytic forages, vegetative propagation has been found to be the most easy and effective method of studies and establishment. The grasses may be studied in the initial phase either in hydroponic or pot systems followed by field trials at relatively larger scale to assess their performance under changing field salinity conditions. Management options can be further studied with different irrigation regimes, fertilizer quantity and quality, harvest periods, and methods of harvests to evaluate optimal productivity.

17.6.2 Scaling-out for Long-term Sustainability

Identification and evaluation of new and alternative crops/species is the first step toward their large-scale adaptation. In many cases, the candidate crops do perform well since the studies are carried out under precisely controlled conditions, but when tested under field conditions (on a relatively sized area), field variabilities influence and may show very different results. The "model farm" approach described in this paper for work at the UAE covers not only the field but also the extreme environmental variabilities. Though the nutritive quality of the new crops/species has not been discussed in this paper, in many cases these variabilities did not show much effect on the quantity (biomass), but they significantly affected the nutrient composition of the crops. The model farm approach also provides reliable data on the long-term productivity of the crops/species but also the time frame for its re-establishment (in case of perennial forages).

Based on such testing procedures, ICBA research has introduced and scaled out many new and alternative crops or species in Middle East to North Africa and West and sub-Saharan Africa, as well as in Central Asia and Caucus and Southeast Asia. Crops that have been scaled out included many annuals such as sorghum, barley, pearl millet, triticale, sunflower, safflower, quinoa, etc. and perennial forages such as *Sporobolus virginicus*, *S. arabicus*, *Paspalum vaginatum*, *Distichlis spicata*, *Acacia ampliceps*, etc. During the last one decade, many medicinal and aromatic plants and other potential crops have been studied suitable for saline environments. Among potential high-value crops also suitable for agroforestry systems include medicinal psyllium (*Plantago ovata*), periwinkle (*Catharanthus roseus*), aloe (*Aloe barbadensis*), celery (*Apium graveolens*), *Jatropha curcas*, *Adhatoda vasica*, and castor (*Ricinus communis*). The important plants yielding aromatic oil include vetiver (*Vetiveria zizanioides*), lemon grass (*Cymbopogon flexuosus*), palmarosa (*C. martinii*), and German chamomile (*Matricaria chamomilla*). Among cut flowers, *Chrysanthemum indicum* has been found most suitable for saline irrigation. Dagar et al. (2004, 2006, 2008, 2009), Tomar et al. (2010), and Dagar (2014, 2018) have evaluated and reported the agronomic practices of many of these crops for salty soils or irrigating with saline water. At times, the cultivars of the same species differ in their salt tolerance as has been found in psyllium (Tomar et al. 2010) and lemon grass (Dagar et al. 2013) where some varieties were found far superior than many others.

17.7 Conclusions

Alternative crops and cropping systems are no more a researchable area for academic and other purposes. It is a need for future agriculture for sustainability and meeting the sustainable development goals (SDG) for closing the food gap and ensuring food security. With changing climatic conditions, land degradation, and water scarcity problems in many agricultural lands globally, it is imperative that marginal lands and water are effectively and efficiently used for crop production. In cases where these resources cannot be used for growing food crops, they can be grown for others like feed, fuel (including biofuel), aquaculture, and others. Freshwater resources have to be limited for growing vegetables and other salt-sensitive crops, while the marginal lands and poor-quality water can be used for growing these salt-tolerant crops to maintain the feed production and in case to supplement on existing production. It is imperative that the new crops are tested by both national and international R&D centers (like ICBA, ICARDA, ICRISAT, CIMMYT, CSSRI, CIP, etc.) and introduced in countries where appropriate.

In addition to identifying the potential crop, its adaptation and domestication remain a challenge both for researchers and policy-makers, since it is highly dependent on the farmer's acceptance and market value chains. DeHaan et al. (2016) proposed the following three-phase domestication pipeline for seed crops but that equally applies to other crops as well.

Phase I: Screening of many plant species to discover candidates. Screening may require several cycles of selection to evaluate evolvability and domestication potential.

Phase II: Each candidate is developed according to one of three general development strategies designed to produce a partially domesticated species usable as a new crop.

Phase III: Domestication proceeds through integration of strategies to develop a commodity crop.

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Engineering and Biological Approaches for Drainage of Irrigated Lands

18

S. K. Kamra, Satyendra Kumar, Neeraj Kumar, and J. C. Dagar

Abstract

Irrigated agriculture, contributing two-fifths of global agricultural production from one-fifth cropped area, is under stress due to associated waterlogging and soil salinity problems. Current annual crop productivity losses due to irrigation-induced salinity are estimated at US$ 27 billion for the world and US$ 1.2 billion for India. Of the 6.74 million ha salt-affected lands in India, severely waterlogged saline soils occur in about two million ha area in arid/semiarid alluvial northwestern states and about one million ha each in coastal and black cotton heavy soil (*Vertisol*) regions. The waterlogging and soil salinity-related losses in irrigation commands of India are likely to magnify severalfold with a projected increase of such areas to 13 million ha by 2025 and to 20 million ha by 2050 due to climate change and enforced use of saline/alkali groundwater in northwestern and southern states.

Besides surface drainage, engineering technologies (subsurface drainage (SSD) and tubewell drainage) and biodrainage through high-transpiring trees are extensively applied for control and amelioration of waterlogging and soil salinity. Considering wide-ranging climatic, soil, geohydrological and outlet conditions, drainage problems and solutions are location specific. While watertable control in fresh groundwater regions is commonly achieved by tubewell pumping, subsurface pipe drainage is almost mandatory in waterlogged and saline groundwater regions. In absence of clear guidelines, there often remains considerable ambiguity in the selection of the most appropriate drainage method for any affected area.

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Basic features of SSD, vertical and biodrainage approaches for management of waterlogged saline-irrigated lands have been presented in this chapter. Since SSD is relatively a new technology in India, a major part of the chapter has been devoted to a historical overview on its progression from small manually installed research studies to large mechanically implemented projects. About 62,000 ha waterlogged saline soils have been reclaimed with SSD in India with significant improvement in crop intensity and yields, land value and farmers' income. Monitoring and evaluation of a number of drainage projects have reiterated that high cost, environmental issues relating to disposal of saline drainage effluent and continuous pumping requirement during post-reclamation phase are the major deterrents to the long-term success of this technology.

Similar to SSD, the technical features and scope of tubewell and biodrainage projects and related variant technologies, developed and evaluated for control of waterlogging and soil salinity in India, are also critically reviewed. The presented variants of vertical drainage system include different types of skimming and recharge structures used for selective abstraction of fresh water floating in a thin layer over native saline groundwater and for disposal of excess flood water from agricultural fields, respectively. Finally, a methodology, based on a watertable depth and groundwater salinity linked criterion, has been presented for implementation of SSD, vertical or biodrainage projects specific to different critically waterlogged saline regions of Haryana.

Keywords

Irrigated lands · Engineering approach · Biodrainage · Subsurface drainage · Vertical drainage · Vertisols · Salt-affected lands · Waterlogging · Skimming and recharge structures

18.1 Introduction

The twentieth century ended with impressive accomplishments in diverse fields of human enterprise, but it has still remained a precursor of nearly one and a half billion people going to bed partially hungry. Population growth, economic progress and rising living standards are leading to growing pressure on land and water resources. Irrigated agriculture, contributing about 40% of global agricultural production from 20% of the cultivated area, is under stress for performance. It faces stiff competition from domestic, industrial and recreational sectors in terms of rising water costs, increased environmental restrictions and reduced irrigation supplies. To aggravate the problem, waterlogging and soil salinization, the age-old nemeses of irrigated agriculture, continue to plague crop productivity in canal-irrigated agricultural areas in several countries (Scheumann and Freisem 2002) including India.

Waterlogging, meaning excess soil moisture in the crop root zone, results from the rise of watertable to within 2 m of soil surface due to deep percolation losses from irrigated fields or seepage from surface irrigation network. In arid and semiarid regions having shallow saline groundwater and high evaporative demand, waterlogging often leads to secondary soil salinity. Saline soils have high concentration of soluble salts (EC_e >4 dS m^{-1}, pHs <8.2 and ESP <15) in the root zone which create different levels of salt and moisture (aeration) stresses to limit crop productivity.

About 20–30 million ha irrigated area in the world is severely affected by waterlogging, soil salinity and sodicity; additional 60–90 million hectares are slightly to moderately affected (Umali 1993; Smedema et al. 2004). Among the key irrigated countries, India, China, the USA, Egypt, Australia and Pakistan have the maximum irrigated and salt-affected area (Ghassemi et al. 1995). The threat to global crop production due to irrigation-induced salinity is serious, and losses at more than US$ 27 billion per year are substantial (Qadir et al. 2014). In the Indo-Gangetic alluvial plains of Indian subcontinent, waterlogging and salinity have dealt a serious blow to agricultural sustainability and farmers' livelihood (Datta and De Jong 2002; Bhutta and Smedema 2007).

Of 6.74 million ha salt-affected lands in India, severely waterlogged saline soils occur in about two million ha area in arid/semiarid northwestern states of Haryana, Punjab, Rajasthan and Gujarat and one million ha each in the coastal and black cotton *Vertisol* regions. The rise of watertable to within 2.0 m depth from soil surface restricts the movement of salts applied with irrigation water and also increases the salinity of groundwater. In arid and semiarid regions having high evaporation rates and inadequate drainage, salts are brought up to soil surface and redistributed unfavourably in the root zone by capillary rise to turn it to a saline soil (Fig. 18.1). It is projected that about 13 million ha area in irrigation commands of India will be affected by waterlogging and soil salinity by 2025; increasing use of saline/alkali groundwater in several northwestern and southern states and the impending climate change may further accentuate the hazard to over 20 million ha by 2050 (TERI 1997; Anonymous 2015).

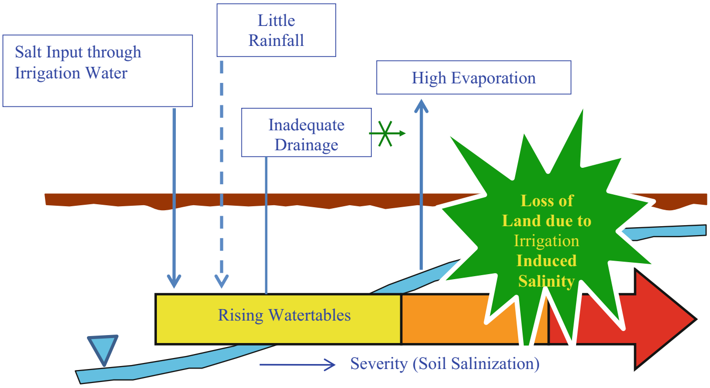


Fig. 18.1 Schematic diagram for development of irrigation-induced soil salinity

The level of reduction in crop yields in an affected area is governed by topography, availability of good-quality irrigation water and depth and salinity status of groundwater and soil. There are earlier reports of 38–77% yield losses of paddy, wheat, cotton and sugarcane due to waterlogging and 40–63% due to high soil salinity and consequent 82–97% reduction in net income in different irrigation commands of India (Joshi 1994) and 58% reduction in net income of cotton in Turkey (Umali 1993). ICAR-CSSRI has estimated the annual crop production and monetary losses due to soil salinity in India as 5.66 million tonnes and INR 80 billion (US$ 1.2 billion), respectively (Sharma et al. 2015).

On-farm or project-level preventive measures like land levelling, micro-irrigation systems, optimizing water allowance, canal lining, establishing biodraining trees alongside of canals, changing cropping pattern and improving surface drainage set-up can be effective to combat or delay waterlogging and soil salinity if implemented before the development of these problems. Curative measures in some form of artificial drainage become inevitable once irrigation-induced waterlogging and soil salinity are developed over large areas.

Though references on land drainage are available in several century-old Indian, Greek, the Netherland, Egyptian, Roman and other western scriptures, this has evolved as an acknowledged technique for watertable and salinity control and for reclaiming agricultural lands since the early twentieth century. Drainage systems are man-made systems that are only implemented when natural drainage is not sufficient to sustain agricultural productivity. Areas with limited natural drainage requiring artificial drainage are usually located in coastal plains, river valleys and inland humid regions where rainfall exceeds evaporation or in arid to semiarid regions where inefficient use and distribution of irrigation water usually lead to waterlogging and secondary salinization.

The drainage methods and techniques vary from one agroecological and socio-economical setting to another (Schwab et al. 1987; Madramootoo and Ochs 1997). Besides surface drainage, other artificial engineering interventions for control of waterlogging and soil salinity in irrigated lands include horizontal subsurface drainage (also called *relief* drains) and vertical subsurface drainage by tubewells, both having a number of variant technologies. Besides these techniques, biodrainage, utilizing the inherent ability of certain deep-rooted trees like *Eucalyptus* to remove excess soil water through rapid transpiration, has been successfully applied for prevention of waterlogging and salinity build-up in irrigated areas in India and several other countries, especially Australia. Both engineering (subsurface drainage and tubewell drainage) and biological (biodrainage) drainage approaches have been applied extensively for control and amelioration of waterlogging and soil salinity in different countries including India. There are, however, no clear guidelines for selection of a drainage method appropriate for any affected area with specific hydrogeological characteristics.

This chapter presents basic features of horizontal subsurface, vertical and biodrainage approaches for management of waterlogging and soil salinity in irrigated lands and progress of these technologies and their variants in India. Finally, a case study is presented for identification of critical and potentially critical waterlogged saline areas of Haryana, most suitable for reclamation through SSD, vertical or biodrainage measures based on a watertable depth and groundwater salinity linked criterion. Surface drainage, though a basic component of any land development and reclamation plan, is not included in this chapter considering the level of socio-economic, environmental and political complexities involved in introducing new surface drainage systems or suggesting modifications in the existing ones.

18.2 Features and Scope of Drainage Systems

All engineering drainage systems have components of field drains and main drainage systems. The field drainage system controls the groundwater level in the field by transferring the excess rain or irrigation water to the main drainage systems which finally dispose it to the outlets of the drainage basins. Field drainage systems can be either surface or subsurface drainage systems. Surface drainage systems consisting of open ditches are most needed when overland flow or water stagnation occurs on the soil surface. Conventional solutions to combat waterlogging and salinity are vertical and horizontal subsurface drainage systems consisting, respectively, of the pumping tubewells or horizontal buried pipes installed at a design slope. While watertable control in fresh groundwater regions is commonly achieved by tubewell pumping, horizontal pipe drainage is almost mandatory in waterlogged and saline groundwater regions. A number of variants of horizontal subsurface drainage system like interceptor drains and pipe less mole drains and of tubewell drainage like different types of skimming wells and recharge structures are commonly used for watertable and or salinity control.

In humid regions the primary goal of agricultural drainage is to lower the water content of the root zone to provide adequate aeration following excessive rainfall or irrigation. A secondary goal is to improve access and trafficability for timely planting and harvesting operations. Open drainage systems are the most common for such conditions but are increasingly being used in combination with subsurface drainage to lower groundwater levels quickly after rainstorms or at the end of the rainy season.

In arid and semiarid regions, the primary goal of agricultural drainage is to remove the accumulated salts from the root zone and to control the secondary salinization by lowering groundwater levels. These goals can be achieved by both pipe and open drains; in most cases pipe drains are the most practical solution. Subsurface pipe drainage systems are further classified as *singular* or *composite* systems. In a singular system, the field drains are buried perforated pipes that discharge into open collector drains. In a composite system, the collector drains also consist of closed or perforated pipes which discharge into an open main drain either by gravity or by pumping.

Most irrigated lands have variable levels of surface drainage in the form of some existing natural drains and a few additionally constructed drains. Subsurface (pipe) drainage systems (Fig. 18.2) are generally used for (i) reclamation of new land with a

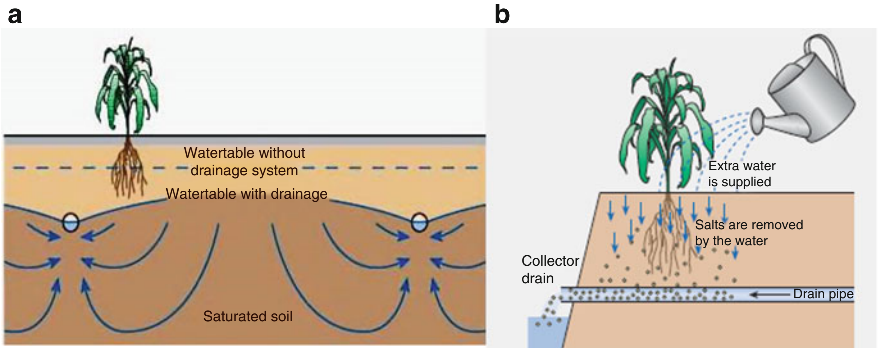


Fig. 18.2 Conceptual diagram of horizontal (pipe) drainage system in irrigated lands. (Figure Courtesy: Nijland et al. 2005)

shallow watertable and/or high soil salinity, (ii) controlling groundwater depth and soil salinity at desired levels and (iii) restoring the productivity of water logged and/or salinized lands to their potential levels. Short-term fluctuations in the watertable are typical in arid and semiarid areas where irrigation is practised. The watertable can rise within a day or two after a surface irrigation and then recede at rates influenced by soil hydraulic properties, irrigation practices, climatic conditions and the depth and spacing of the drains.

A tubewell drainage system consists of a network of shallow or deep tubewells to lower the watertable, including provisions for running the pumps and surface drains to dispose of the excess water. Tubewell drainage is used in areas with a high soil permeability and preferably fresh groundwater that can be reused for irrigation. While all vertical drainage systems continuously need electric or diesel power supply for pumping and horizontal systems dispose drainage effluent under gravity or by pumping, the biodrainage trees dispose excess water through high transpiration using solar energy.

Surface Drainage: Surface drainage is the most important drainage technique in the humid and subhumid zones where overland flow is the major component of excess water movement to major drains or natural streams. The technique normally involves the excavation of open trenches/drains and is most commonly applied on heavier soils where excess rainfall cannot percolate fast through the soil profile to the watertable because of slow infiltration rates. One day water stagnation due to absence of adequate surface drainage measures can result in 2–8% losses of crop yields; the corresponding losses may be as high as 20–48% for 6 days water stagnation (Bhattacharya 2007). A surface drainage coefficient of 5–7 $l\ s^{-1}\ ha^{-1}$ has been reported to provide adequate safety to most sensitive *Kharif* crops against waterlogging in humid regions having ~1000 mm annual rainfall in India. Bhattacharya (2007) also reported that investments on surface drainage are economically viable with yield benefits ranging from 20 to 28% in sugarcane, 20 to 25% in paddy, 32% in gram and 50% in Indian bean.

Subsurface Drainage (SSD) System: SSD has been accepted globally as a viable technology to combat the problem of waterlogging and soil salinity and to ensure the sustainability of irrigated agriculture. It is anticipated that SSD will be needed in 3–5 million ha area in the next 25 years to meet global food requirements (Smedema 2000). While the USA, China and Australia developed and extensively adopted SSD technologies for irrigated lands over the past 80 years (Smedema et al. 2004), Egypt, Pakistan, Turkey and India have been investing heavily on research and development of this technology for the past 40 years (Ritzema and Schultz 2011). Among developing countries, Egypt stands as the country with more than 2.5 million ha area provided with subsurface drainage (Nijland 2000).

Although there have been impressive progress and technical improvements to standardize the SSD technology for improving the productivity of affected irrigated lands, organizational and institutional aspects of drainage projects have also proved to be equally important for its long-term success. High cost, environmental issues relating to disposal of saline drainage effluent and continuous pumping requirement during post-drainage phase in pumped outlet cases are some of the deterrents to long-term success of this technology. There are several reports of serious environmental degradation in terms of increasing levels of river/seawater pollution (salinity, selenium toxicity) and loss of biodiversity due to discharge of polluted drainage water from irrigated lands in Imperial Valley and San Joaquin Valley in California (USA), Aral Sea Basin in Russia, Indus Basin in Pakistan and Murray-Darling Basin in Australia (Cervinka et al. 1999). Involvement of farmers, sharing of construction and operating cost and government subsidy are also vital aspects. Drainage of waterlogged saline soils in low-lying depression areas without a suitable disposal outlet is much more challenging.

Pace of implementation of SSD projects in India and other developing countries has to accelerate significantly to improve productivity potential of waterlogged saline areas and economic wellbeing of resource poor farmers. Preservation and restoring the productivity of irrigated agriculture without environmental degradation is a challenging task and demands regional planning and management perspectives.

Vertical Subsurface Drainage: Vertical subsurface drainage refers to the technique of controlling the watertable and salinity in agricultural areas. It consists of removal of groundwater through pumping, from a single or a multiple well system, an amount of groundwater equal to the drainage requirement. The success of tubewell drainage depends on many factors, including the hydrogeological conditions of the aquifer, physical properties of the overlying fine-textured layers and quality of groundwater being pumped. Enough water has to be removed from the aquifer to produce the required drop in hydraulic head, and for vertical downward flow, the hydraulic conductivity of the overlying layers must be such that the watertable responds sufficiently quickly to the reduced head in the aquifer.

For tubewells to be effective in draining agricultural land, the transmissivity T of an unconfined aquifer ($T = KD$, where K is hydraulic conductivity and D is thickness

Table 18.1 Minimum required thickness of aquifer for tubewell drainage

Mean hydraulic conductivity (m d^{-1})	Minimum required aquifer thickness (m)	Transmissivity (m^2 d^{-1})
43	14	602
26	25	650
17	40	680
13	60	780

McCready (1978)

of aquifer) should be ideally more than 600 m^2 day^{-1} (McCready 1978) to ensure an economic spacing and yield of the wells. For semi-confined aquifers, a further condition is that the hydraulic resistance c of aquitard overlying aquifer ($c = D'/K'$, where D' is thickness and K' is hydraulic conductivity of aquitard) should not be more than 1000 day (Table 18.1).

Early attempts to use a series of pumped wells for land drainage and salinity control were made in the USA and former USSR more than 80 years ago. If the water in the pumped aquifer is of good quality, it can be used for irrigation. The Indus Plains of Pakistan is a notable example of using 3800 public tubewells and over 200,000 low capacity private tubewells for land drainage, salinity control and supply of irrigation water, though with limited long-term success, as a part of Salinity Control and Reclamation Projects (SCARPs) implemented during 1960–1995 (Qureshi and Berrett-Lennard 1998). A review of studies and experiments with tubewell drainage in various countries shows that this technique cannot be regarded as a substitute for the horizontal SSD system. For instance, there are many areas like lower Sindh in Pakistan where tubewells would not function in absence of favourable aquifers. Unlike the other SSD systems, tubewell drainage is not economically feasible in small areas because of the too much water drained out of the area that consists of groundwater flowing in from surrounding areas.

Though Mohtadullah (1990) mentioned that tubewells were a better economic choice than horizontal drains for the Indus Basin, it is generally accepted that horizontal drains have lower construction and operation costs (Zhang 1990) for small to medium areas. In saline areas where the groundwater salinity increases substantially with depth, tubewells would provide more saline drainage effluent and over longer period than horizontal subsurface drains. This occurs since the streamlines towards the well occur deeper in the aquifer than those towards pipe drains or ditches (Fig. 18.3), thus posing more serious disposal and related environmental problems. In SSD systems, salinity of groundwater in the drainage area and of drainage water improves after salts from the soil profile and upper groundwater layers had been drained out. This replacement period is much longer in tubewell drainage, where pumping affects much deeper layers of groundwater.

Mole Drainage: Heavy soils of low hydraulic conductivity (< 0.01 m day^{-1}) often require very closely spaced drainage systems (2–4 m spacing) for effective watertable control, making subsurface drainage systems excessively expensive.

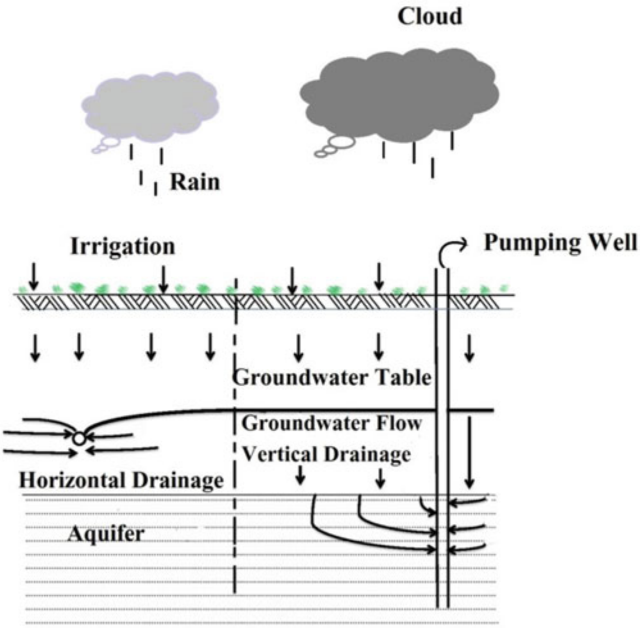


Fig. 18.3 Flow pathways of water and salts in subsurface and tubewell drainage systems

Under such conditions, techniques like mole drains have proven useful alternative to surface drainage (Hopkins and Colac 2002; NRCS 2003). Mole drains are unlined circular channels installed at a depth in the soil profile which function like pipe drains. These are formed in the clay subsoil by pulling a solid cylinder, with a wedge-shaped point, through the soil at a defined slope and depth without digging a trench. During installation, the soil in the vicinity of the mole channel should be moist enough to form a channel but not too dry to break up or too soft to form slurry.

Mole drains are generally installed at 40–60 cm depth and 2–10 m spacing, 4–8 m being the most accepted depth range. Based on a 4-year study involving mole drain spacing of 2–6 m in black cotton *Vertisol soils* in Bhopal region of India, an optimum mole drain spacing of 4 m has been recommended for the soybean crop (Singh and Ramana Rao 2014). The success of mole drainage is dependent upon stability of the mole channel, and it remains open for water entry for a reasonable period of time. Currently mole drainage systems are most commonly used for removing excess water from the surface layers in perched watertable situations in stable clay soils.

The major advantage of mole drains is lower cost for installing drains at very close spacing and shallower depths despite needing frequent renewals after only a few years. Successful application of mole drains as a temporary SSD system for reclaiming saline and saline *sodic* soils has been reported (Spoor et al. 1990), while the scope for extending mole drainage into new areas is provided by Spoor (1994).

Jha and Koga (2002) presented an excellent review of the use of mole drains in combination with subsurface drainage systems in the world.

Interceptor Drains: To protect flat areas from flooding by surface runoff or shallow subsurface outflows from adjacent higher grounds, an interceptor drain can be constructed at the foot of these uplands. For areas of 2–2.5 ha, the interceptor drains can be constructed like terraces and as grassed waterways for large areas. A drain depth of 0.45 m and 0.70 m^2 cross-sectional area are considered minimum values. A silt trap can be constructed on the upslope side of the ditch to prevent clogging of interceptor drains.

Interceptor drains are also used to intercept seepage from canal network which significantly impacts the quantum and distribution of surface and groundwater resources of the area. Canal seepage is influenced by the cross section of canal, nature and quality of canal lining, the hydraulic gradient between the canal and surrounding land, any impermeable layer at or near the canal bed, water depth, flow velocity and sediment load (FAO 1977). However, as per thumb rules, canal seepage is estimated at 20–30% of the canal flow in unlined and 15–20% in lined canals. Open drains, pipe drains and bio-interceptor drains have been used to intercept canal seepage to restrict the damage to a limited area, lessen the degree of damage and allow reuse of the intercepted water. Though open interceptor drains have not been found effective in Pakistan and in Chambal command of India because of poor maintenance and obstructions made in the drain by farmers to store water, limited experience with piped interceptor drains is encouraging.

Biodrainage: It refers to a technique of lowering groundwater in waterlogged areas by raising tree plantations. It is a preventive technique to avoid the development of salinity and waterlogging problem in canal commands. The technique is highly useful when the soil salinization has not still occurred due to rise in groundwater level (Chhabra and Thakur 1998; Jeet Ram et al. 2007; Dagar et al. 2016). For command areas, planting of 100 m or wider belt along the canals on both sides with high water-demanding trees such as *Eucalyptus*, *Populus*, *Leucaena* and *Bambusa* (Singh 2009; Dagar et al. 2016) and grasses such as species of *Spartina*, *Panicum*, *Leptochloa* and *Brachiaria* for the interspaces can be helpful in controlling waterlogging problem. An integrated drainage system comprising of subsurface drains, tree belts (biodrainage), evaporation-cum-fish ponds and agroforestry-based systems seem promising for the amelioration of waterlogged saline soils in areas without adequate outlets in the states of Haryana, Punjab and Rajasthan. Trees along canals help in checking seepage in adjacent agricultural fields.

Selection Criterion of SSD or Tubewell Drainage System

Under the assumption that a reliable source of energy is available for pumping, a methodology for selection of either subsurface (pipe) or tubewell drainage for any waterlogged saline irrigated area, based on depth of watertable, quality of groundwater and aquifer transmissivity as adapted from Bos (2001), is presented in Fig. 18.4. The information on infiltration rate of soil, topography, hydrogeology,

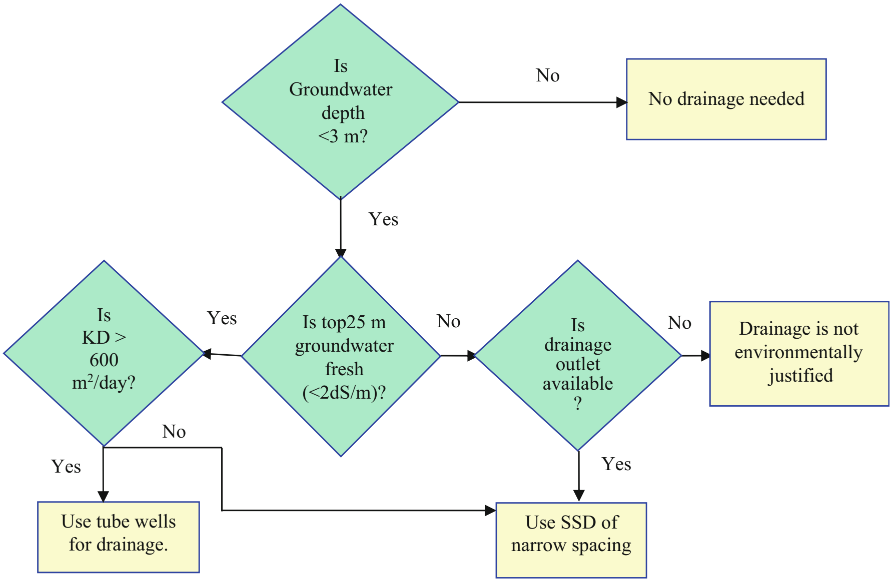


Fig. 18.4 Selection methodology of subsurface drainage method in irrigated land in semi arid climate. (Adapted from Bos 2001)

precipitation, evapotranspiration, irrigation supplies and grown crops is also needed to take a well-considered decision on the selection of either drainage method. No drainage system is needed in the irrigated area if the watertable is deep (at >3.0 m) and thus prevents salt accumulation in the root zone of the irrigated crop. Water balance studies in semiarid areas indicate that deep-percolating irrigation water causes a rising groundwater table if the ratio of potential evapotranspiration and total (irrigation and precipitation) applied water is less than 0.6 (Bos et al. 1991; Bastiaanssen et al. 2001). This emphasizes efficient use of irrigation water applied by surface methods or shifting to micro-irrigation systems to avoid the need for a costly drainage system in future.

If the top (say 25 m) groundwater layer in irrigated semiarid regions is fresh, tubewells will serve the dual purpose of drainage as well as irrigation. For this reason, the salinity of the groundwater should be sufficiently low (< 2 dS m^{-1}), tolerable to most crops without significant yield reduction. If the top layer of the groundwater cannot be used (either directly or mixed with fresh water) and yet needs to be discharged, availability of a drainage outlet is mandatory to consider SSD system. However, the expected benefits of drainage must be weighed carefully against potential damages to downstream users due to discharge of saline drainage water into surface water supplies. If a disposal outlet is available, selecting a horizontal narrow spacing SSD system is recommended to ensure the best possible water quality for downstream users. Flow lines in a SSD system can extend to one-fourth depth of the drain spacing; wide drain spacing is likely to mobilize a much thicker layer of saline groundwater than a close spacing system. If groundwater can be used for irrigation or other purposes, it is still to be ascertained if the transmissivity KD of the aquifer exceeds 600 m^2 day^{-1} to allow continuous pumping by tubewells at 30 l s^{-1} discharge (Kruseman and De Ridder 1971).

18.3 Progress of Subsurface Drainage, Vertical Drainage and Biodrainage Projects in India

As discussed in earlier sections, the productivity of irrigated agriculture can be sustained for a long time with proper leaching practices and adequate drainage to remove the accumulated salts and keep the watertable deep enough to prevent capillary rise of salts into the root zone. Two types of subsurface drainage, horizontal and vertical, are employed to control watertable and/or soil salinity. To control the watertable, it is necessary to attain an equilibrium between the groundwater recharge and draft. Recharge can be reduced by lining of canals and water courses and also by better farm management and judicious use of canal waters. Draft can be regulated by horizontal drainage system consisting of shallow open ditches or pipes laid horizontally at design depths below land surface or by vertical drainage system consisting of open wells, shallow and deep tubewells and related variant technologies. Biodrainage is a biological measure to prevent or delay the development of waterlogging and/or soil salinity in the irrigation commands.

Progress of horizontal subsurface drainage, vertical drainage, biodrainage and related variants and tradeoffs is presented for India in this section.

18.3.1 Subsurface Drainage

Subsurface drainage (SSD) is an effective technology for the amelioration of waterlogged saline-irrigated lands by maintaining watertable below desired depth and draining excess water and salts out of the area. The technology developed by CSSRI during 1980s initially for Haryana has been widely adopted and replicated in Rajasthan, Gujarat, Punjab, Andhra Pradesh, Karnataka and Maharashtra. These research efforts have resulted in the development of a package of practices, consisting of providing appropriate subsurface drainage, leaching of salts and management of saline drainage effluents for reclamation and management of waterlogged saline soils.

A SSD system consists of an underground network of open ditches or filter covered pipe drains installed at designed depth and spacing below the ground surface to remove excess water and salts from the affected fields. It involves three categories of drains: the laterals, the collectors and the main drains. *Lateral drains*, laid parallel to each other at designed spacing, depth and gradients, cover the entire field, accept excess groundwater whenever it rises above drain level and carry it to the *collectors* which further bring it to the main drain. The main drain carries the water to the outlet from where it is disposed out of the area either by gravity or by pumping from a sump well that allows temporary storage of some volume of drainage water. Other components of the system include manholes/inspection chambers, pump house and dewatering pump set. In areas with low soil permeability or high rainfall intensities or where surface water is the main problem, open ditches are preferred. Subsurface drains are preferred in high permeability areas where excessive water in the soil is the main problem.

The most common materials used in the manufacture of lateral drain pipes are clay, concrete and plastic. Clay and concrete pipes (often referred to as tiles), used earlier when PVC pipes were not available, are usually made in lengths of 30 cm and 10 cm internal diameter. The water enters the pipeline through the gaps between the tiles. These have now been totally replaced by PVC pipes which come in smooth and corrugated forms. The length of PVC pipes varies from about 6 m in case of smooth rigid pipes to 200 m in case of corrugated, flexible pipes available in coils which can be joined by sockets. Water entry into smooth pipes is via slit cuts or punched in the walls, while corrugated pipes have small openings in the valley of the corrugations. Perforations of 1–2 mm ϕ are usually provided in about 2–3% of the surface area of the pipe.

The advantage of plastic pipes over clay and concrete is their considerably lighter weight and their productions in larger lengths, thus involving lower transport cost and cheaper installation. The collector and main drains are either of pipes or open ditches. Bigger diameter RCC or PVC pipes joined together with sockets are generally used for collector drains. The joining of laterals to the collector through *manholes* helps in the maintenance of drain lines. The lateral drains are laid at a slope of 0.05–0.1%, while collectors are generally laid at a slope of 0.1%. The *sump* must have adequate storage capacity below the level of entry of the collector drain to avoid the continuous operation of the pump.

Two design variables of a SSD system are drain spacing and drain depth, which control the watertable depth. The depth and spacing of drainage system are governed by rainfall, irrigation, hydrogeology, soil texture and outfall conditions in the affected area. Other factors influencing the watertable height and thus drain spacing include drainage coefficient, representing the volume of water to be drained dependent upon regional water balance of the drainage area, hydraulic properties of soil and aquifer and cross-sectional area of the drains. Several equations relating these factors to drain spacing are available. The depth of lateral drains is influenced by the required watertable levels (for optimum crop production and for preventing soil salinization), the texture of different soil layers and the depth within the reach of available drainage machinery.

In general, the depth of drains may be limited between 1.5 and 2.0 m. The length of lateral drains varies from 200 to 500 m (ideally <300 m) depending on available natural slope and layout of the area. Envelope (filter) materials are provided around the pipe drains to facilitate water flow into the drain and to prevent the entry of soil particles into the drain. In absence of synthetic filters, graded gravel envelopes were used in the 1980s, but these have been replaced by synthetic filters which have considerable advantage over gravel in terms of transportation and installation.

Drainage water is disposed under gravity or by pumping into main drains, stream, canals or evaporation ponds.

18.3.1.1 Manually Installed SSD Projects

Though a few manually installed feasibility studies on SSD were conducted in the past by different research organizations in nonsaline and saline soils in different parts of India, systematic multidisciplinary research on SSD was initiated by CSSRI during early 1980s. A pilot research project on investigations, design, manual installation, monitoring and impact analysis of SSD in terms of watertable control, reduction in soil salinity, improvement in crop yields, cost- benefit analysis and management of saline drainage water was conducted by CSSRI during the period from 1983 to 1995 in 10 ha waterlogged saline area at village Sampla in district Rohtak of Haryana (Rao et al. 1986). About 20 similar pilot studies of 30–120 ha area each were conducted by CSSRI and other state departments during the 1980s and 1990s for amelioration of waterlogged saline soils in the states of Haryana, Rajasthan, Gujarat, Andhra Pradesh and Karnataka.

At most of these sites, the watertable fluctuated between about 1.5 m from ground level during summer to near the surface during monsoon. The initial salinity of groundwater at most sites was more than 10 dS m^{-1}, being as high as 40 dS m^{-1} in extreme cases. In the earlier installations, cement clay tiles were used for laterals and cement concrete pipes for the collectors. However, after 1986, PVC rigid and corrugated pipes are being increasingly used as subsurface drains. Either graded natural gravel or PVC (synthetic) netting (60–75 mesh size) has been used as envelope at these sites. The saline drainage effluent was pumped into surface drains or canal distributaries.

At most sites, drains were installed at about 1.5 m depth; the maximum adopted drain depth being 1.75 m. The average salinity of root zone at all the sites reduced considerably resulting in a good production of a number of crops in hitherto barren highly saline lands. The installation of subsurface drainage has continuously reduced the soil salinity and salinity of drainage water and significantly increased yields of different crops.

The manually installed SSD technology developed by the CSSRI during 1980s initially for Haryana has been widely adopted and replicated through mechanical installation in about 62,000 ha farmers' fields in Rajasthan, Karnataka and Maharashtra Gujarat, Punjab and Andhra Pradesh. This was facilitated in a major way through two international Indo-Dutch projects on land drainage operational at CSSRI during 1983–2001. These research efforts have resulted in the development of a package of practices, consisting of providing appropriate subsurface drainage, leaching of salts, crop production and management of saline drainage effluents for reclamation and management of waterlogged saline soils. Based on the experience of manual subsurface drainage projects, the following observations can be made:

- The reclamation of waterlogged saline soils with subsurface drainage is a technically and economically feasible solution since it leads to considerable increase in cropping intensity and crop yields and shifts to more remunerative cropping pattern.

- Subsurface drains at 65–80 m spacing and 1.5–1.8 m depth can provide adequate watertable and salinity control for potential crop production in waterlogged saline soils. For arid regions of Haryana and Rajasthan, drain spacing up to 100 m can be tried.
- Research output, from field studies and extensive numerical modelling results (Kamra et al. 1991, 1992), contributed to acceptance of shallower drains (1.4–1.8 m) in arid and semiarid regions of India and other countries.
- In areas with suitable outlets, rainwater leaching through drainage during the rainy season is adequate to maintain the favourable salt balance of drained fields. The quality of drainage effluent improves after 1–2 years to levels suitable for possible use in irrigation. After reclamation leaching, the watertable rise due to the suspension of drainage during non-rainy season can contribute up to 50% crop water needs (Rao et al. 1992).
- Reuse of drainage water for irrigation of salt-tolerant crops is an option to handle large volumes of saline drainage effluent. Drainage waters of about 10 dS m^{-1}salinity can be used directly or in conjunction with canal water in blending (mixing) or cyclic (sequential application) mode for irrigation of barley, wheat and mustard in the winter season. Salts added through use of saline drainage water were leached down with monsoon rains or by a pregermination irrigation with canal water (Sharma et al. 1994).
- In inland areas without an outlet, evaporation ponds with the surface area of about 5–10% of the drainage area offer an interim solution for managing saline drainage effluent. The quality of pond water deteriorates with time, and seepage losses can be significant during initial years in ponds constructed in the sandy substratum (Kamra et al. 1996).
- Analysis of financial feasibility of manually installed SSD projects indicated a benefit: Cost ratio of 1.26 and viable internal rate of return of 13.3% (Datta et al. 2000).

18.3.1.2 Mechanically Installed SSD Projects

During the mid-1990s, CSSRI was involved in monitoring and evaluation of two mechanically installed subsurface drainage projects of about 1000 ha each in Gohana and Kalayat blocks of Haryana executed by Department of Agriculture of Government of Haryana with assistance of the Netherlands Government. A number of SSD projects of 800–1200 ha pilot area each have been implemented in about 10,500 ha area in farmers' fields in Haryana where annual potential loss due to waterlogging and soil salinity is estimated at more than INR 10000 million. Besides Haryana, the subsurface drainage technology has been widely adopted and replicated in about 62,000 ha area in India, mainly in Rajasthan, Gujarat, Punjab, Andhra Pradesh, Maharashtra and Karnataka in some of which CSSRI has been/is involved (Table 18.2). About 16,500 ha areas in Chambal irrigation command in Rajasthan

Table 18.2 First estimate of area provided with subsurface drainage in different states under government schemes (needs updating)

State	Irrigation command	Area (ha)
Haryana	Western Yamuna Canal, Bhakra Canal	10,500
Rajasthan	Chambal, Indira Gandhi Nahar Pariyojana	16,500
Maharashtra	Lift irrigation system of Krishna River; Neera canal command, uncommanded	3500[a]
Karnataka	Upper Krishna, Tungabhadra, Malprabha, Ghatprabha	25000[a]
Punjab	Sirhind Canal (Southwest Punjab)	2500
Manual (small projects in different states, including above states)	Andhra Pradesh and Telangana (Nagarjuna Sagar, Krishna Western Delta); Gujarat (Mahi Kadana, Ukai Kakrapar); Kerala (acid sulphate soils); Assam (tea gardens), Madhya Pradesh (Tawa, Chambal, Barma command)	4000
Total		62,000

[a] In addition to above government-supported projects, SSD has been installed in more than 20,000 ha area by local farmers without government support

were provided with SSD with Canadian assistance during the period from 1991 to 2001. A drain spacing of 35–60 m, drain depth of 1.2 m and gravity outlet were the design parameters of the adopted SSD system (Sewa Ram et al. 2000). Extensive monitoring and evaluation indicated 40–50% increase in the yield of soybean and wheat over non-SSD sites resulting in a benefit-cost ratio of 2.6 and an internal rate of return (IRR) of 28% (Sewa Ram et al. 2000). Tejawat (2015) reported that the SSD system is working well after 20 years of installation and bringing in 15–20% additional financial benefits for farmers as compared to non-SSD area.

The implementation of SSD heavy soils of Maharashtra and Karnataka picked up rapidly from 2005 onwards with entry of private sector in SSD projects, almost exponentially with liberal funding under RKVY after 2007. During the past 5 years, CSSRI has been instrumental in getting SSD projects approved and implemented in about 4000 ha waterlogged saline area in Haryana, 2000 ha in Maharashtra and 1000 ha in Karnataka with funding under RKVY and other governmental schemes. More than 3000 ha affected area in Maharashtra and Karnataka has been reclaimed by SSD by farmers themselves without government support with drainage water disposal into open drains under gravity. About 20,000 ha area in Karnataka has been reportedly provided with SSD in a hybrid mode (manual + land shaping machinery like JVC) by different agencies and farmers. Southwest Punjab is in urgent need of SSD and other salinity management technologies like biodrainage and saline fisheries for which comprehensive regional salinity management planning and reclamation are mandatory.

Kamra (2013) summarized the improvement in crop yields in SSD projects implemented in different states of India (Table 18.3). It was reported that SSD increased cropping intensity by 40–50%, farm income by 200–300% resulting from enhanced yields of paddy (> 50%) and of wheat and cotton (> 100%) and by

Table 18.3 Impact of subsurface drainage on crop yields in different states

State	Crop	Crop yield (Mg ha^{-1})		
		Before drainage	After drainage	Increase over pre-drainage (%)
Haryana (3 locations)	Cotton	0.0	1.4–1.8*	**
	Wheat	0.0–3.1	1.9–4.9*	18–112
	Barley	0.0	2.1–4.2*	**
	Paddy	1.4	1.7	21
	Pearl millet	0.88	1.2	39
Andhra Pradesh (2 locations)	Paddy	3.6–3.7	5.2–5.6	45–50
Gujarat (1 location)	Sugarcane	78–104	105–140	35
Karnataka (7 locations)	Paddy	1.4–4.0	3.7–8.4	98–340
	Cotton	3.3	10.4	215
	Sunflower	3.0	7.4	146
	Sorghum	6.8	11.6	70
	Wheat	4.0	6.7	68

*Effect of drain spacing during first year; ** difficult to estimate increase in originally highly saline soil with zero production (> 100%)

Table 18.4 Design parameters of subsurface drainage for different regions of India

Drainage coefficient (mm d^{-1})			Drainage depth (D_d)		Drain spacing (D_s)	
Climate	Range	Optimal	Outlet	D_d (m)	Soil texture	D_s (m)
Arid	1–2	1	Gravity	0.9–1.2	Light	100–150
Semiarid	1–3	2	Pumped	1.2–1.8	Medium	50–100
Subhumid	2–5	3			Heavy	30–50

50–100% in most other crops. The socio-economic analysis of SSD indicated cost-benefit ratio of 1.5, IRR of 20% and employment generation of 128 man-days per ha every year (Kamra and Sharma 2016; Ritzema et al. 2008; Gupta 2002; Datta et al. 2000; Sewa Ram et al. 2000). Further, the finalized design parameters (drainage coefficient, drain spacing and depth) of SSD systems for different regions of India, synthesized from outcome of two Indo-Dutch drainage projects coordinated by CSSRI (Ritzema et al. 2008; Kamra 2013), are presented in Table 18.4.

Bundela et al. (2016) presented a detailed analysis of cost of installation of SSD systems at 50–100 m spacing in coarse- and medium-textured soils (clay $\leq$30%) and at 20–50 m spacing in heavy-textured soils (clay $\geq$30%). The cost of funding of SSD projects has been recommended as INR 74000 ha^{-1} and INR 79000 ha^{-1} for drain spacing (D_s) of 67 m and 60 m, respectively, and pumped outlet in medium-textured soils of Haryana and other northwestern states. Corresponding cost at 30 m drain spacing with a gravity outlet for heavy soils in Maharashtra, Karnataka, Gujarat and other *Vertisol* regions has been recommended at INR 111500 ha^{-1}.

18.3.1.3 Performance of SSD Projects in Haryana State

Out of 10,584 ha area provided with SSD over the last two decades in Haryana, more than 8000 ha has been installed in the past 12 years. Currently, CSSRI is associated with design, monitoring and evaluation of five SSD projects implemented by Haryana Operational Pilot Project (HOPP) of Ministry of Agriculture in 600–1000 ha area in Rohtak, Jhajjar, Jind and Sonepat districts. The basic design parameters of SSD projects in Haryana include a drainage coefficient of 1.5 mm day^{-1}, lateral drain spacing of 60–67 m and 1.5 m depth, corrugated PVC pipes of 75 and 100 mm ϕ for laterals and 160–294 mm ϕ for collectors as per ASTMIDIN standards and geo-synthetic filter with $O_{90} > 300$ on laterals and Nylon sock of 60 mesh on perforated collectors. Brief critical results on the performance of some SSD projects are presented to highlight the salient observations:

- Activities under HOPP are quite comprehensive involving detailed investigations starting from identification of the problem areas, preparation of designs, layout and cost estimates of SSD projects for funding and implementation of the project.
- HOPP has three sets of laser-controlled trencher and bucket excavators (Fig. 18.5) and supporting machines. Each fleet of machines installs subsurface drains in 300–400 ha area depending upon breakdowns or unexpected rains during summer (mid-April to end June) working months when watertable is below 1.5 m.
- Due to less concrete progress on construction of pump house, distribution of pump sets to farmers' societies and farmers' participation in post-reclamation pumping of drainage water, the improvements in crop yields and economic return have remained non-satisfactory at a number of SSD projects in Haryana.
- The technology provides a net present worth of about INR 65000 ha^{-1} with benefit-cost ratio of 1.76 and internal rate of return 20%. The material and mechanical installation costs cover about 60% and 40% of the total cost.

Despite above bottlenecks in efficient pumping of drainage water, significant improvement in watertable control, reduction in soil salinity and improvement in crop yields were observed in selected blocks of certain SSD projects where pumping was initiated either by HOPP or individual farmer's efforts. Pathan (2015) used EM38 technique to evaluate the effectiveness of SSD in improving soil salinity in

Fig. 18.5 Subsurface drainage machinery being used in Haryana

38 ha area of block JD 4 at Siwanamal SSD site in Jind district where adequate pumping had been done by a farmer. GPS-coordinated EM38 surveys were conducted during 2015 to measure apparent electrical conductivity (EC_a) at 50 m × 50 m grid and correlated with salinity analysis of collected soil samples at selected locations. EM survey results of 2015 were compared with similar EM survey conducted by CSSRI in the same block during 2012 (before installation of SSD) to evaluate the impact of SSD on salinity distribution in 60 cm soil profiles. EC_e maps of composite 0–60 cm soil depth for JD 4 (pumping) block are presented for 2012 and 2015 in Fig. 18.6, while differences in salinity levels in different depth zones are presented in Table 18.5.

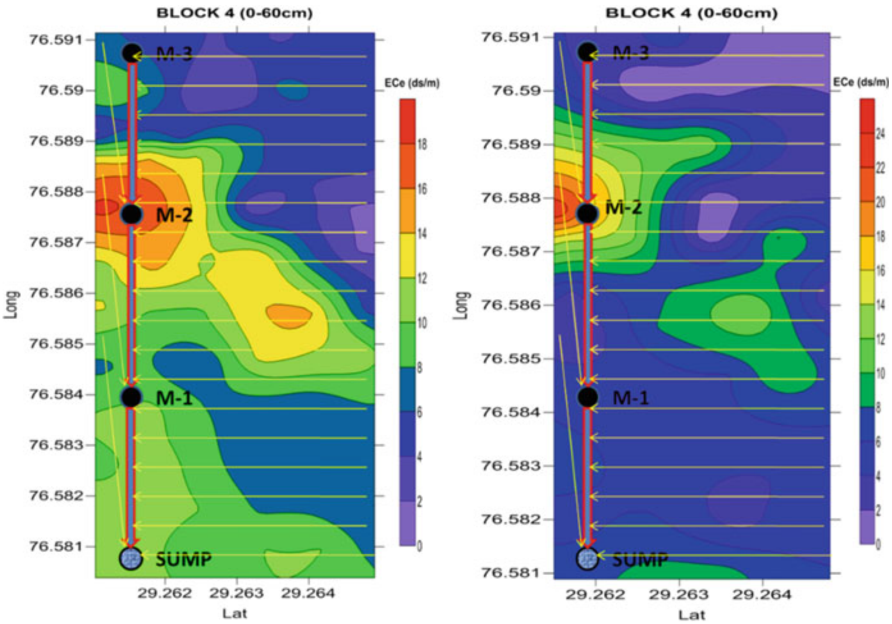


Fig. 18.6 Spatial map of improvement in soil salinity in 0–60 cm depth in JD 4 block of Siwanamal before (2012) and after (2015) installation of SSD

Table 18.5 Improvement in percent area under different soil salinity levels in block JD 4 at Siwanamal SSD site

		EC_e <4 dS m^{-1}	EC_e 4–8 dS m^{-1}	EC_e 8–16 dS m^{-1}	EC_e >16 dS m^{-1}
Depth	Year	Area %	Area %	Area %	Area %
0–15 cm	2012	01.3	21.8	66.2	10.7
	2015	20.5	54.3	23.2	2.0
0–30 cm	2012	02.9	25.4	63.9	7.7
	2015	17.6	37.2	35.6	9.6
0–60 cm	2012	06.6	34.6	56.4	2.4
	2015	18.7	46.0	30.0	5.3

Table 18.6 Pumping status and crop yields in different SSD blocks at Siwanamal SSD (2015–2016)

Drainage block No.	Pumping status	Yield (Mg ha^{-1})	
		Rice	Wheat
JD 1	No	1.5–2.0	1.0–1.5
JD 6	No	2.0–2.5	2.5–3.0
JD 2	Functioning	4.0–4.5	3.5–4.0
JD 4	Functioning	4.5–5.0	4.0–4.5
JD 3	Partial	3.5–4.0	2.5–3.0
JD 5	Partial	3.5–4.0	4.0–4.5
JD 7	Partial	3.5–4.0	3.0–3.5

Table 18.7 Benefit-cost ratio of major crops before and after SSD at Banmandori (district Fatehabad, Haryana)

Crop	Benefit-cost ratio		Percent increase
	After drainage	Before drainage	
Rice	1.42	0.92	54.3
Wheat	1.26	0.85	32.7
Cotton	1.13	0.82	37.6
Mustard	1.22	0.87	40.3

It can be seen that 98.7% and 97.1% area having more than 4 dS m^{-1} salinity in 0–15 cm and 0–30 cm layer during 2012 reduced, respectively, to 79.5% and 82.4% area during 2015 due to SSD activities. Similarly, the area having more than 8 dS m^{-1} salinity in 0–60 cm zone reduced from 58.8% to 35.3% during the same period.

Overall status of SSD project and crop yields of rice (CSR 30) and wheat (Pusa 1121) during 2015–2016 is summarized in Table 18.6. It is seen that the yields of rice and wheat crops in functional (pumping) blocks (JD 2 and JD 4) are almost double over those in non-pumping blocks (JD 1 and JD 6), while the yields of partially functional blocks fall in between the two extremes. There is widespread awareness about the effectiveness of SSD in ameliorating waterlogged saline soils, and it is expected that with efforts of farmers themselves, the crop yields in fully and partially functional blocks will rise to the levels of normal soils. Similar results have been reported for other SSD sites in Haryana (Kamra and Sharma 2016).

For another SSD site of 277 ha at Banmandori in Fatehabad district of Haryana, Raju et al. (2015) presented an economic analysis on gross income, total cost and net income before and after implementation of SSD. The benefit-cost ratio for different crops (Table 18.7) indicate that benefit-cost ratio was less than one for all crops before drainage which improved to 1.42 for rice, 1.26 for wheat, 1.13 for cotton and 1.22 for mustard after introduction of SSD. An increase of 32–54% in benefit-cost ratio due to SSD indicates the worthiness of the technology for reclaiming waterlogged saline soils for the study area in Haryana. It is to be mentioned that farmers insist on going for paddy crop in waterlogged saline areas of Haryana due to not only better benefit-cost ratio but also because of more favourable marketing policies for paddy than other *Kharif* crops.

The operational cost of the drainage system in northwestern states is mainly due to pumping of the drainage effluent. After 1 or 2 years of operation of the drainage system, the quality of drainage effluent improves to a level where it can be reused for irrigation. High costs, socio-economic and environmental issues relating to disposal of saline drainage effluent, need of community participation for system operation and existing institutional/organizational constraints are the major deterrents to rapidly increase the pace of reclamation projects (Ritzema et al. 2008). Involvement of farmers, sharing of construction and operating cost and government subsidy are vital to the success of SSD technology. Adoption of this technology is quite slow keeping in view the quantum of the problem and despite tangible benefits in terms of productivity gains and on-farm employment generation. Major institutional and organizational changes and new business models are needed for expediting the implementation of SSD projects, especially in northwestern Indian states.

18.3.1.4 Disposal and Management of Saline Drainage Water

Subsurface drainage waters generally contain high concentrations of soluble salts and plant nutrients and may sometimes also contain potentially toxic trace elements and pesticides. The disposal and storage of such waters can have remarkable impacts on the degradation of surface and groundwater quality; a threat to aquatic organisms, wildlife and plants; and potential risk to public health (Heuperman et al. 2002). Discharge of drainage water from irrigated lands in the San Joaquin Valley in California (USA) into the Kesterson Reservoir resulted in problems of selenium toxicity in the biota (Cervinka et al. 1999).

Depending on the location, hydrology and topography of the drainage basin, the possible methods for disposing saline drainage water in Northwest India include (i) disposal into regional surface drainage system which is ultimately linked with major rivers flowing through the region, (ii) pumping into the canal distributaries that carry high flow discharge for most of the year and (iii) disposal into evaporation ponds in land-locked depression areas not having a suitable drainage outlet. Options of disposal of saline drainage water into canal distributaries are covered briefly here while of biodrainage are covered separately in another section of this chapter. Details on other alternatives like evaporation ponds, reuse for cropping or agroforestry, shallow watertable management, saline aquaculture and the use of salt-tolerant varieties can be found in Kamra (2015). The large-scale drainage disposal and reuse programs, however, will need substantial infrastructural changes and consideration of maintaining a favourable basin-level salt regime.

18.3.1.5 River Discharge with and Without Dilution

Disposal of the drainage water into rivers or canal can deal with large volumes and may be a practical medium-term solution for the inland sites. Discharge to the river system is inexpensive, but the disposal of large volumes of saline drainage effluent through this mode is likely to become increasingly difficult due to environmental restrictions imposed by downstream users. The maximum drain discharge generally occurs during the rainy season when the irrigation demands are relatively less, and consequently large volumes of saline drainage water can be discharged into the river

Table 18.8 Allowable subsurface drain discharge and drainable area into Yamuna River

	Drain discharge $m^3\ s^{-1}$ using drainage water of EC_d		Drainable area (ha) using drainage water of EC_d	
Month	6 ($dS\ m^{-1}$)	10 ($dS\ m^{-1}$)	6 ($dS\ m^{-1}$)	10 ($dS\ m^{-1}$)
June	0.9	0.5	5000	3000
July	25.4	14.4	146,000	83,000
August	47.6	27.0	274,000	156,000
September	6.5	3.7	37,000	21,000
October	3.0	1.7	17,000	10,000

EC_d is electrical conductivity of drainage water

system. This will necessitate establishment of numeric water quality standards for various points along the river, monitoring and modelling of spatial and temporal water quality trends and provisions for diverting saline drainage waters produced away from the surface drain/canal/river.

During the monsoon (July to September) season, the flow of the Yamuna River exceeds 1000 $m^3\ s^{-1}$, and its salinity is less than 0.2 $dS\ m^{-1}$, while the salinity of water flowing in the surface drains is also low at 1.2 $dS\ m^{-1}$. In a case study on the disposal of drain discharge into the Yamuna River during June to October, UNDP (1985) estimated the volume of SSD water of 6 and 10 $dS\ m^{-1}$ that could be discharged safely in Yamuna without exceeding the salinity of river water after mixing beyond 0.75 $dS\ m^{-1}$. Based on 80% frequency discharges of the river at Wazirabad (Delhi) and of Surface Drain No. 2 and 8 of Haryana, allowable discharge of subsurface drainage water was calculated.

Assuming a subsurface drainage surplus of 1.5 m $ha^{-1}\ day^{-1}$ during the monsoon period, the area that could evacuate its drain discharge into the river was calculated (Table 18.8). It is seen that 83,000 ha and 156,000 ha critically waterlogged area in Haryana can evacuate 10 $dS\ m^{-1}$ drainage water in Yamuna River during July and August, respectively. It was also reported that in the winter months, low river flows (< 50 $m^3\ s^{-1}$) reduce the disposal capacity considerably. The disposal requirements during this period can be reduced through interventions like shallow watertable management and the reuse of drainage water.

18.3.2 Vertical Drainage

As discussed in an earlier section, vertical drainage is a technique of controlling the watertable and salinity in agricultural areas. It consists of pumping, from a series of wells, an amount of groundwater equal to the drainable surplus. Tubewell drainage enables the watertable to be lowered to a much greater depth than horizontal drainage system. If the water in the pumped well is of good quality, it can be used for irrigation. However, if the pumped water quality is not of good quality, then its disposal and management is much more difficult than other drainage systems.

As a general guideline, it can be stated that vertical drainage systems cannot be used to control waterlogging if groundwater is saline and the salinity increases with depth. However, some variants of vertical drainage systems, called groundwater skimming structures, can be used in a limited way to pump out water from thin layers of fresh water floating over saline groundwater in coastal and inland-irrigated areas. In this paper, basic features of a few skimming structures and other vertical drainage variants like open well and groundwater recharge wells are discussed in the context of Indian conditions.

18.3.2.1 Groundwater Skimming Structures

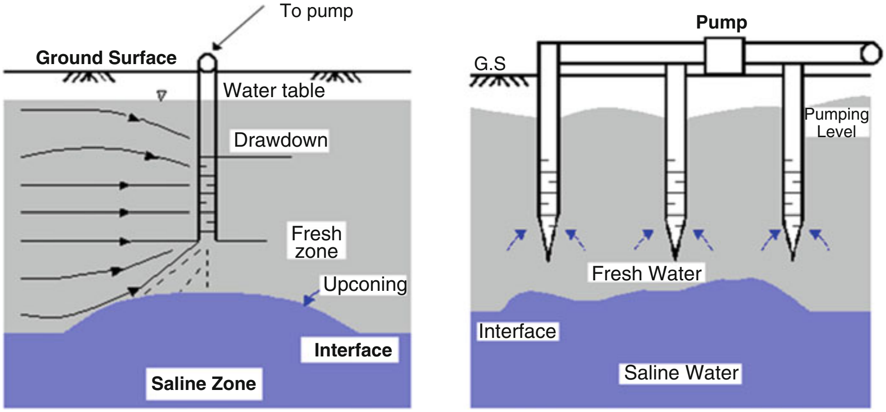
Excessive pumping of fresh groundwater to meet increasing domestic, irrigation and industrial requirement is causing extensive seawater intrusion problems in coastal areas or groundwater salinization in several inland-irrigated regions of India. A 2–3 % mixing with seawater renders fresh water inappropriate for human consumption and for irrigation, while a 4% mixing is enough to destroy a freshwater resource (Custodio 1997). The local effect of such activities is a gradual deterioration in pumped groundwater quality due to up-coning or rise of relatively more saline groundwater of deeper layers to within the domain of pumping wells. Under these conditions, it is imperative not to disturb the saline water but to selectively skim fresh water accumulated over the native saline groundwater by tubewells or some modified forms of vertical drainage and by enhancing groundwater recharge.

Various skimming well configurations such as single, multi-strainer, radial collector and scavenger wells (Fig. 18.7) are possible to selectively abstract fresh water from thin layers overlying saline groundwater. The basic concept of all skimming structures is to modify the flow lines in such a way to maximize horizontal contribution of aquifer zones of acceptable quality to pumped water (Sufi et al. 1998).

(i) *Single Well*

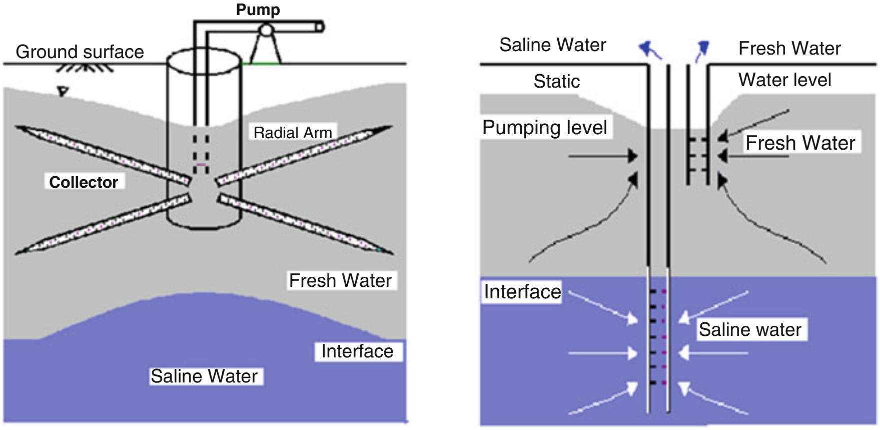
A single well (Fig. 18.7a) is commonly used in unconfined aquifers in most parts of India. While using these wells in saline groundwater regions, well penetration is kept deep into the freshwater layer with a large gap between the bottom of the well and the fresh-saline water interface. As a general rule, the depth of the well-considered safe for extracting fresh water by a strainer tubewell without disturbing the saline water is 1/3rd of the total depth of the freshwater zone. Single tubewell-based drainage projects were executed during the 1980s and 1990s at Masitawali in Indira Gandhi Nahar Pariyojana (IGNP) (Hooja et al. 1995), Ghaggar depression areas in Rajasthan and in Fatehabad branch area of Haryana for watertable control in the vicinity of canal distributaries. In Rajasthan, the water quality was deteriorating with depth, while in Haryana the vertical drainage projects were commissioned to lower watertable in waterlogged areas.

The waterlogged project sites in Haryana were mostly selected along the canal distributaries and irrigation channels where a layer of fresh water floated over deeper saline water zone. A number of pilot projects involving single tubewell-type structures were implemented by Haryana State Minor Irrigation and Tubewell Corporation (HSMITC) (Table 18.9). Strainer tubewells of 6–10 $\mathrm{l\ s^{-1}}$ were used at most sites, while at some sites cavity tubewells were used. The pumped water of



a) Single well

b) Multi-Strainer well



c) Radial collector well

d) Scavenger well

Fig. 18.7 Different types of fresh water skimming wells

acceptable quality was discharged into nearby distributaries to successful lowering of watertable and enabling farmers to get normal crop yields. Continuous pumping of years in a few projects caused negligible increase in pumped water salinity.

Ironically such projects have not been implemented in later years, perhaps due to lack of proper guidelines (as discussed in this paper) for selection of subsurface drainage or tubewell drainage in waterlogged saline areas.

(ii) *Multi-strainer Well*

A multi-strainer well (Fig. 18.7b), with relatively shallower penetration than single well, can be used for watertable control with diminished *up-coning* in freshwater layers of restricted depth. The system consists of closely spaced interconnected wells, each of low capacity, pumped by a central suction pump.

Table 18.9 Vertical drainage schemes executed by HSMITC in Haryana, India, and impact on watertable control

S. No.	Scheme	District	Cost (million INR*)	Period	Watertable decline (m)
1	Narwana area (11 drainage tubewells, 88 ha area)	Jind	1.99	1985–1992	1.00–4.00
2	Rori area (8 shallow tubewells, 70 ha area)	Sirsa	2.10	1985–1992	1.90–3.00
3	Fatehabadbranch (50 drainage tubewells)	Fatehabad	6.10	1995–1996	0.44–3.20
4	Kishangarh sub-branch/link channel (50 drainage tubewells)	Hisar	6.10	1995–1996	0.95–1.90
5	Jui feeder/canal (15 drainage tubewells)	Bhiwani	1.83	1996–1997	0.65–2.18

*1 US$ = 72 INR

Such structures are reported to be extensively used close to canals/distributaries in Punjab in India (Shakya 2002) and in the Indus Plains of Pakistan (Sufi et al. 1998; Mazhar Saeed et al. 2003) and also for draining foundation pits.

A multiple well point system was installed and evaluated for tapping floating thin layer of good-quality water near a canal distributary without creating turbulence in the lower saline water zone in 100 ha project area in Golewala in Faridkot district of Punjab, India (Shakya 2002). It consisted of a number of well points arranged in a line and interconnected to each other through a horizontal pipe line (lateral) installed at about 0.7–1.0 m below ground level to be pumped centrally by one pumping unit (Fig. 18.8). The total discharge from the system was divided equally over the well points so that the requirement of prime mover will be the same as is required by single well.

The above design was further improved (Shakya 2002) to include a siphon system for automatic pumping of water brought by laterals to a centrally located sump of 2 m depth. The moment the water is lowered in the sump through pumping, groundwater starts moving from well points to the sump under siphon action. Length of the lateral should be limited to 350 m to minimize priming problems. There are reports on the use of these systems in marginally saline regions of Haryana, Rajasthan, Andhra Pradesh and Tamil Nadu in India. Air leakage and priming problems have been reported from most of these studies. Sufi et al. (1998) reported that the double-strainer skimming well to be the most promising skimming technique for the studied area in Pakistan.

(iii) *Radial Collector Well*

Radial collector wells consisting of an open well and input radial drains on one or more sides (Fig. 18.7c) involve shallower penetration than a single vertical well operating at the same discharge. Since the radial drains collect water from shallow depths, up-coning of saline water from lower depths is prevented. Large diameter

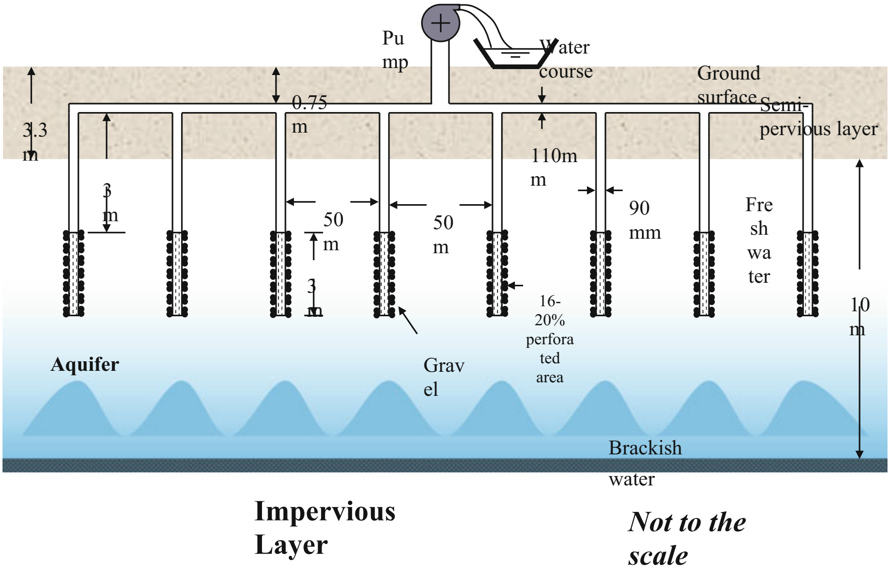


Fig. 18.8 Schematic diagram of multiwell point system installed at Golewala (Shakya 2002)

Fig. 18.9 Installation of radial collector D*oruvu* wells at Bapatla (Andhra Pradesh), India

open skimming wells experimented at Hisar in Haryana (Kumar and Singh 1995) and at Luni-Ki-Dhani in Rajasthan (Hooja et al. 1995) and a drain line-sump-based *Doruvu* technology embarked on a large scale in coastal sandy soils of Andhra Pradesh (Raghu Babu et al. 2004) are the local variants of radial collector wells.

About 0.174 million ha coastal sandy area in Andhra Pradesh and 0.68 million ha in Tamil Nadu, having 700–1200 mm annual rain, is characterized by existence of 8–10-m-thick sandy layer of fresh water followed by a clay layer saturated with saline water. Radial collector well-type *Doruvu* skimming structures (Fig. 18.9) consist of an open well of 1.2–1.5 m diameter with radial subsurface drains (at 2.4–4.0 m depth and of 30–40 m length on two sides) for skimming of fresh groundwater. The system yields a discharge of 5–15 $l\ s^{-1}$ or more depending upon the number of arms and nature of sand and can operate in combination with sprinkler/drip system. Pumping tests indicated 90 m as the safe spacing between two skimming wells. Such structures can meet *rabi* crop water demand of 2 ha area using sprinklers and have 1.7 benefit-cost ratio and 30% internal rate of return

(NATP 2006). The tracer studies revealed that radial arms contribute 80% of pumped water, while the remaining 20% comes from the bottom of the well.

The D*oruvu* technology was found to increase the farmers' income by 25–40% due to enhanced crop yield, but a major deterrent for large-scale adoption among small and marginal farmers had been the high cost and lack of optimal designs and layouts for sustained supply of fresh water. The technology has been widely adopted in Guntur and Prakasam districts of Andhra Pradesh. Horizontal drilling of radial drains needs to be standardized for sandy soils to reduce the cost of installation of these structures.

(iv) *Scavenger Wells*

Scavenger wells (Fig. 18.7d) involve simultaneous abstraction of fresh and saline waters through two wells having screens in different quality zones, for controlling the rise of interface. The scavenger wells have been tested in the lower Indus Basin of Pakistan (Sufi et al. 1998) and have shown their potential in skimming of fresh water. Despite apparent problem of disposal of saline water, the scope of scavenger wells needs testing for cases involving two cavity wells (non-strainer tubewells common in saline groundwater regions of Indo-Gangetic plains) installed at different depths or a combination of a strainer and a cavity wells. Geological, hydrological and geochemical characteristics of the aquifers must be studied in an integrated way to study the hydraulics and evaluate the performance of these skimming structures. In interconnected layers, the pumping from lower saline zone is likely to increase the fresh water recharge potential of upper zone.

Based on the principle of scavenger wells (Fig. 18.7d), Kamra et al. (2006) installed and evaluated the performance of a skimming cum recharge structure constructed at a downstream location prone to runoff flooding at village Jagsi in district Jind of Haryana. The system consisted of two cavity tubewells, installed at 7 m and 40 m depth in the respective fresh and saline groundwater zones, which could be operated separately or together to obtain water of different qualities. A recharge chamber of 6 m × 2.5 m × 2 m size and containing a graded filter of fine sand, coarse sand, gravel and boulders was constructed close by to facilitate recharging of one or both cavities with filtered runoff during rainy season or excess canal water. The objective was to increase the availability of good water in upper cavity or improve the quality of lower cavity for possible use at time of water scarcity. General improvement was reported in the groundwater regime of area due to combined effect of the natural and imposed recharge interventions. The estimated recharge rates through injection in cavity wells were low at about one-third of the pumping rates under shallow groundwater conditions.

18.3.2.2 Groundwater Recharge Wells

The sustainability of highly productive but water-intensive rice-wheat cropping system in Haryana and Punjab is getting threatened due to alarming decline of watertable, increase in pumping cost and deterioration in groundwater quality. The rate of groundwater decline can be slowed down by change in cropping pattern or by enhancing groundwater recharge (GR). Besides raising groundwater level, GR also helps in utilizing flood water that goes waste or causes damage to standing crops and also in improving groundwater quality. About two-third area of Haryana and one-third each of Punjab and Gujarat are underlain with saline groundwater, a major part by high residual sodium carbonate (RSC) waters. For such and areas having problems of fluoride contamination, groundwater recharge structures can help in improving water quality by dilution.

Under two Ministry of Water Resources (GOI) funded projects, CSSRI developed the design of small groundwater recharge (GR) wells (shafts and cavities) and installed and monitored such structures at 60 low-lying farmers' fields in declining watertable and poor-quality groundwater alluvium regions of Haryana (38), Punjab (5), UP (5) and Gujarat (12) during 2008–2012. In these and earlier works on groundwater recharge of CSSRI (Kaledhonkar et al. 2003; Kamra 2013), the groundwater recharge structures consisted of a bore well (for carrying water to subsurface sandy zones) coupled to a recharge filter consisting of layers of coarse sand, small gravel and boulders in a small brick masonry chamber. Selection of recharge structures of different designs, depths and costs was based on hydrogeological investigations and quantum of potential runoff water available at specific locations. Despite semiarid climate at selected sites, there are depression areas where water accumulates during rainy season and can be recharged to groundwater as a local vertical drainage system to save crops from submergence due to heavy rain.

Of all tested recharge structures under these projects, recharge cavity (Fig. 18.10) has been found to be the most effective and practical for individual farmers' needs (Kamra 2013). It consists of a conventional cavity pumping well coupled with a recharge filter and hence can be used also for occasional pumping. It is constructed by drilling a bore hole until a sandy layer is found below a clay layer. A blind PVC

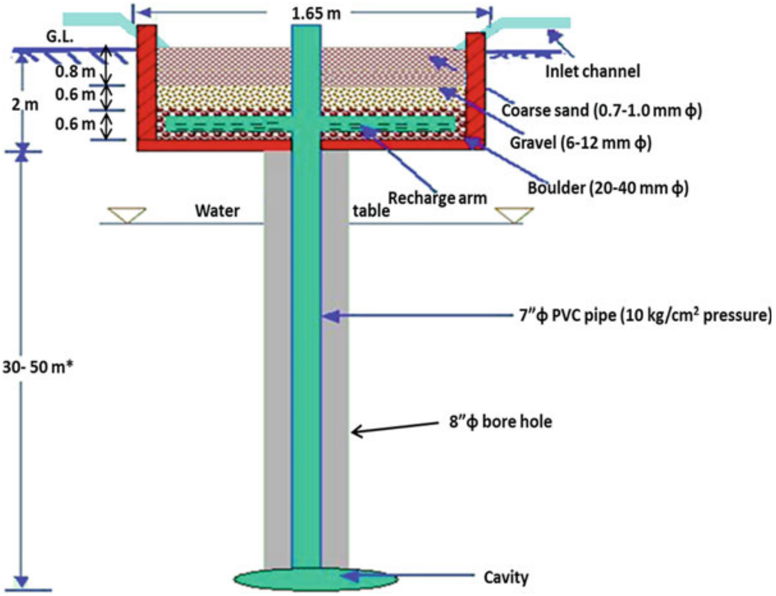


Fig. 18.10 Design features of a groundwater recharge cavity tubewell

casing pipe of 7–9 inch ϕ (7 inch in Fig. 18.10) is drilled into the clay layer, and sand is pumped out until a stable cavity is developed below the clay layer. To safeguard against clogging, the surface runoff is first passed through a recharge filter consisting, respectively, of 0.8 m, 0.6 m and 0.6 m thick layers of coarse sand, small gravel and boulders in a small brick masonry chamber as per details provided in Fig. 18.10.

GR wells, having intake rate of 4–6 litre sec^{-1}, were found effective in augmenting groundwater, improving its quality and enhancing the farmers' income by saving submerged crops. The structures helped in reducing flood volumes to save transplanted rice in the lowest 1–2 ha area at certain sites in Haryana and Punjab resulting in a net saving of 25,000/ from rice only. Recharge wells in Gujarat also resulted in prolonged availability and improvement in quality of groundwater that facilitated increase in income of INR 30000–75,000 ha^{-1} in mango, papaya and banana plantations. The payback period of 30–45 m deep recharge structures and costing INR 30000–50,000 ha^{-1} (2008 prices) was estimated as 1–2 years. The field observations in a farmer's field in Karnal district during heavy rains of August 2012 clearly indicated a recharge structure to be essential for saving maize crop from adverse effect of prolonged water submergence.

Groundwater recharge structures also provided impressive perceptible benefits like improvement in salinity, alkalinity and fluoride concentration at selected sites in four states. The clogging of the recharge filter is a major constraint in the performance of recharge structures. Kumar et al. (2012) reported that the thickness of upper sand layer of recharge filter was the primary factor influencing clogging, while size of gravel in the middle layer also influenced effectiveness of sand as a filter. Practical effective designs of recharge filters and quality of water being recharged are the focus of current research at CSSRI.

18.3.3 Biodrainage

Biodrainage refers to a technique of lowering groundwater in waterlogged areas by making use of evapotranspiration power of plants, especially of trees. It is a preventive technique to avoid the development of salinity and waterlogging problem in canal commands. The technique is highly useful when the soil salinization has not still occurred to a serious level in canal commands due to rise in groundwater level (Chhabra and Thakur 1998; Heuperman et al. 2002; Jeet Ram et al. 2007, 2011; Dagar et al. 2016). Strip plantations of *Eucalyptus tereticornis* prevented the development of shallow watertables and salinity, while adjacent fields lacking tree cover recorded an upward movement of water (Jeet Ram et al. 2007, 2011; Dagar et al. 2016). Dagar (2011, 2014) reported *Casuarina glauca*, *Acacia ampliceps*, *Terminalia arjuna*, *Pongamia pinnata* and *Syzygium cuminii* as other species suitable for block plantations in waterlogged areas.

Fast-growing species, like cloned *Eucalyptus*, poplar and bamboo having high water consumption under excess soil moisture conditions, are suitable for biodrainage (Jeet Ram et al. 2007; Dagar 2014). Of these, *Eucalyptus tereticornis*, a fast-growing deep-rooted tree species, is most commonly used for lowering of watertable and seepage control from canals in waterlogged areas. So far, *Eucalyptus* has been found as the most efficient species for lowering down of watertable (Dagar et al. 2016). A major factor determining the sustainability of biodrainage projects is attainment of long-term salt-balance in the soil profile in shallow saline groundwater regions. The water use and transpiration capacity of trees and other crops decrease with increase in water salinity; it reduced to one-half of potential at 8 dS m^{-1} water salinity in *Eucalyptus* species as compared to normal water (Oster et al. 1999).

Jeet Ram et al. (2011) evaluated the performance of clonal *Eucalyptus tereticornis* planted on field boundaries in a 5 ha land-locked waterlogged area surrounded on three sides by canal branches at Puthi, Hisar district in Haryana (India). The paired row strip plantations at 1 m × 1 m spacing on field boundaries 66 m apart at plant density of 300 plants ha^{-1} were monitored through 22 observation wells for groundwater use and watertable control. These plantations resulted in lowering of shallow groundwater by 0.85 m in 3 years and by ~ 2 m after 5 years. It was also reported that in area planted with *Eucalyptus* trees, wheat yield was 2.15 Mg ha^{-1} as compared to 0.64 Mg ha^{-1} in nearby fields without tree plantations. Dagar et al. (2016) further compared different density of strip plantations and concluded that spacing of 1 m × 1 m is profitable and ideal for strip plantation on acre line to lower down the watertable. This has been adopted by farmers in quite large area in Punjab and Haryana (Fig. 18.11). In another trial (Patil et al. 2005), biodrainage proved an effective option to intercept seepage by trees planted along a canal and water courses. Species such as *Acacia nilotica*, *Dalbergia sissoo*, *Sesbania grandiflora* and *Casurina equisetifolia* intercepted, respectively, 86%, 84%, 72% and 72% of canal seepage in saline Vertisols regions of India.

Fig. 18.11 Biodrainage through strip plantations of *Eucalyptus tereticornis* on field boundaries on farmers' fields in Haryana. (Photos: JC Dagar and Surender Lathwal, DFO Haryana Forest Department)

For canal command areas, planting of 100 m or wider belts of high water-demanding trees such as *Eucalyptus*, *Populus*, *Leucaena* and *Bambusa* along the canal and grasses such as *Spartina*, *Panicum*, *Leptochloa*, *Brachiaria*, *Phragmites*, *Panicum* and *Paspalum* for the interspaces have been recommended for controlling the waterlogging problem (Singh 2009; Dagar 2014). Of late, combined applications of biodrainage and suitable land modifications are being explored to productively utilize the waterlogged salt-affected soils. Heuperman et al. (2002), however, reported apprehensions on the long-term success of biodrainage in controlling harmful build-up of root zone salinity in canal commands without additional drainage measures. This advocates research and pilot studies on the scope of this technology in combination with other drainage or salinity management measures like subsurface drains, evaporation - cum - fish ponds and agroforestry-based systems. Such integrated drainage measures seem promising for the reclamation of waterlogged saline soils in areas without adequate drainage outlets in the states of Haryana, Punjab and Rajasthan.

18.4 Identification of Areas Suitable for Different Drainage Methods in Haryana

Kamra and Sharma (2016) reported that shallow watertable existed within 1.5 m in more than 50,000 ha area in Haryana in 2013 which had almost turned into waste land, while additional 3,80,000 ha area under 1.5–3.0 m watertable depth was potentially waterlogged saline land. Under ICAR-Emeritus Scientist scheme entitled ‘Developing a regional framework and guidelines for effective operation and governance of subsurface drainage projects in Haryana’ of the senior author operational at CSSRI, Karnal, CGWB data of November 2015 has been further synthesized in the form of GIS maps and watertable depth and groundwater quality for waterlogged regions of Haryana. These maps have been overlaid by surface elevation and surface drainage network maps to identify priority areas for implementation of SSD, biodrainage and vertical drainage projects. Brief results on watertable depth and groundwater quality for November 2015 are presented in Fig. 18.12 and Tables 18.10 and 18.11, respectively.

Most of the critically waterlogged (WTD < 1.5 m) and potentially waterlogged (WTD 1.5– 3.0 m) areas occur in arid and semiarid regions in central inland depression basin of Haryana encompassing Jhajjar, Rohtak, Sonipat, Jind, Fatehabad, Bhiwani, Kaithal and Hisar districts. Out of 74,595 ha critically (0–1.5 m) waterlogged area, above seven districts account for 62% or 46,415 ha area, while remaining 38% ha area falls in Ambala and Yamuna Nagar districts which have relatively higher annual rainfall and consequently less susceptibility to soil salinization and a few other districts in south and northwest Haryana.

Similarly, about 334,902 ha (83%) out of total 403,890 ha potentially waterlogged lands (watertable 1.5–3.0 m) of Haryana occur in above seven districts. Districts Jhajjar, Rohtak and Sonepat have the highest percentage of waterlogged area; Rohtak and Jhajjar have watertable within 3.0 m depth in 53% and 45% area,

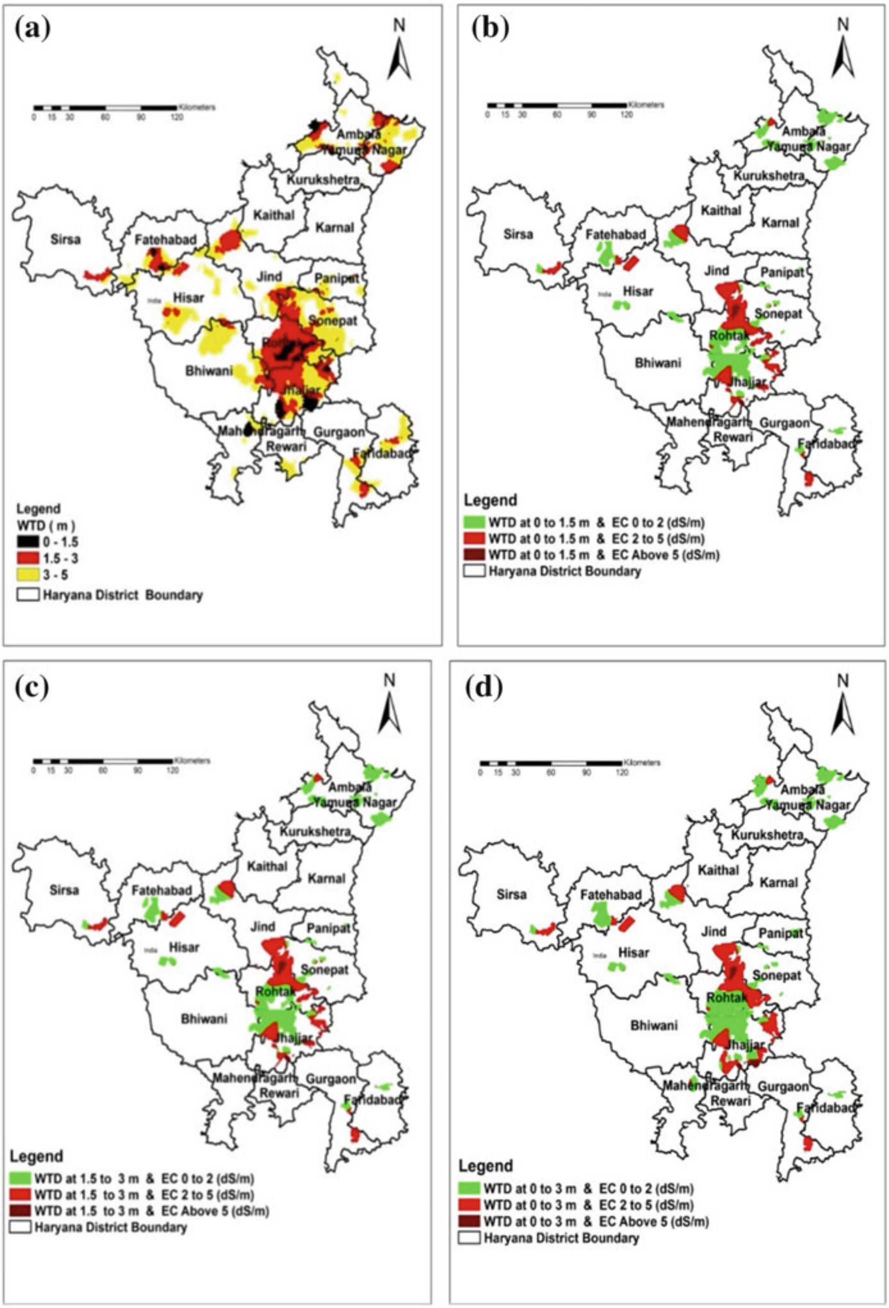


Fig. 18.12 (**a**) Shallow watertable depth WTD (**a**) and associated groundwater salinity regions for 0–1.5 m (**b**), 1.5– 3.0 m (**c**) and 0.0–3.0 m (**d**) depth areas of Haryana

Table 18.10 Area under different watertable depths in different districts of Haryana (November, 2015)

District	Geographical area × 100 (ha)	Area (ha) under watertable depth			% District area under watertable depth		
		0–1.5 m	1.5–3.0 m	0–3.0 m	0–1.5 m	1.5–3.0 m	0–3.0 m
Central Haryana							
Jhajjar	2111.9	26,530	69,424	95,954	12.6	32.9	45.5
Rohtak	1685.1	9020	80,850	89,870	5.4	48.0	53.4
Sonepat	2213.4	–	78,191	78,191	0.0	35.3	35.3
Jind	2732.0	–	42,326	42,326	0.0	15.5	15.5
Fatehabad	2398.0	9613	19,533	29,146	4.0	08.1	12.1
Bhiwani	4632.6	–	19,112	19,112	0.0	04.1	04.1
Kaithal	2299.7	1252	8759	10,011	0.5	03.8	04.3
Hisar	4166.8	–	16,707	16,707	0.0	04.0	04.0
Total (central Haryana)	22239.5	46,415 (62.2)[a]	334,902 (82.9)[a]	381,317 (79.7)[a]	2.1 (1.05)[a]	15.1 (7.6)[a]	17.2 (8.7)[a]
Kandi (Ambala, Panchkula, Yamunangar) and remaining other districts							
Total (other districts)	21773.13	28,180 (37.8)[a]	68,988 (17.1)[a]	97,168 (20.3)[a]	1.3 (0.6)[a]	3.2 (1.6)[a]	4.5 (2.2)[a]
Grand total	44012.63	74,595	403,890	478,485	1.7	9.2	10.9

[a] % of state area

Table 18.11 Status of area under shallow watertable depths and different groundwater salinity (EC_{gw} in dS m^{-1}) in Haryana (Nov. 2015)

District	Area (ha) under WTD (0–1.5 m)			Area (ha) under WTD (0–3.0 m)		
	EC_{gw} = 0–2 dS m^{-1}	EC_{gw} = 2–5 dS m^{-1}	EC_{gw} = > 5 dS m^{-1}	EC_{gw} = 0–2 dS m^{-1}	EC_{gw} = 2–5 dS m^{-1}	EC_{gw} = > 5 dS m^{-1}
Jhajjar	8200	16,330	2000	43,740	48,180	4030
Rohtak	19,580	6270	–	64,650	40,060	2010
Sonepat	–	–	–	9080	20,600	2830
Jind	–	–	–	9910	23,450	–
Gurgaon	–	–	2350	3090	7030	2350
Mahendragarh	5410	970		5410	970	–
Hisar	–	–	–	7940	8770	–
Ambala	5420	–	–	26,310	2680	–
Bhiwani	70	–	–	12,270	2540	–
Fatehabad	4070	–	–	18,920	1780	–
Yamuna Nagar	140	–	–	20,170	–	–
Panipat	2640	–	–	4020	–	–
Sirsa	–	–	–	2320	6510	
Faridabad	–	–	–	3310	–	–
Total (Haryana)	46,159 (1.0)*	23,570 (0.5)	4350 (0.1)	232,770 (5.3)	133,260 (3.0)	11,220 (0.26)

*Figures in parenthesis in district or Haryana rows indicate % of district or state area, respectively.

while Sonepat, Jind and Fatehabad have such conditions in 35%, 15% and 12% area of respective districts. Assuming 80% of critical waterlogged saline area and 10% of potentially waterlogged area are to be in need of improved drainage, it is estimated that 70,000 ha area need subsurface drainage in these districts, a major part in Rohtak, Jhajjar and Sonepat districts. These are rough estimates, and exact figures may differ depending upon public investments made on implementing/improving existing surface drainage network in coming decades.

For selecting priority areas for implementation of SSD, vertical and biodrainage projects, salinity of groundwater and availability of a suitable outlet for drainage water are other requisites besides shallow watertable conditions. Maps of groundwater salinity were superimposed on watertable depth map (Fig. 18.12a) to derive maps (Fig. 18.12b–d) and areas (Table 18.11) having shallow watertable depth (0–1.5 m and 0–3.0 m) and having salinity from 0–2.0 dS m^{-1}, 2–5 dS m^{-1} and more than 5 dS m^{-1}.

It is seen that out of 46,415 ha critically waterlogged (WTD < 1.5 m) area in Haryana, 2000 ha in Jhajjar has $EC_{gw} > 5$, while 16,330 ha in Jhajjar and 6270 ha in Rohtak district have EC_{gw} of 2–5 dS m^{-1}. Similarly, about 1.1 lakh ha (1 lakh = 100 thousand) area in four districts of Jhajjar, Rohtak, Sonepat and Jind districts have WTD of 1.5–3.0 m and groundwater salinity of 2–5 dS m^{-1}, while 6870 ha area in first three districts have EC_{gw} more than 5 dS m^{-1}, highlighting more severe waterlogging and soil salinity problem needing urgent remedial measures like SSD projects. Other issues like availability of canal water for leaching and suitable outlet for disposal of drainage water are being considered in the above-mentioned project along with above aspects to suggest priority areas for implementation of SSD projects in Haryana.

Similarly, out of 74,595 ha area having watertable at 0–1.5 m depth, 46,159 ha have good-quality groundwater with $EC_{gw} < 2.0$ dS/m which are ideal sites for biodrainage. About 60% of such areas are distributed in Jhajjar and Rohtak districts in central Haryana followed by a few other districts like Mahendragarh, Ambala and Fatehabad. Similarly, out of 478,485 ha area having watertable between 0 and 3.0 m depth, about 50% (232,770 ha) has good-quality groundwater with $EC_{gw} < 2.0$ dS m^{-1}. Those areas in central Haryana having watertable within 0–3 m and groundwater salinity 0–2 dS m^{-1} sites are suitable for biodrainage, while those in other parts of Haryana are recommended for biodrainage, and some forms of vertical drainage provided aquifers in those areas have transmissivity of more than 600 m^2 d^{-1}. All above and other issues like availability of drainage outlets for disposal of saline effluents from SSD projects are being integrated to identify priority locations for implementation of SSD, vertical drainage and biodrainage projects for amelioration of waterlogged saline lands in Haryana.

18.5 Summary and Recommendations

Performance of irrigated agriculture, contributing about two-fifth of global agricultural production from less than one-fifth cultivated area, is getting degraded severally by the problems of waterlogging and soil salinization. Current annual losses in crop productivity due to irrigation-induced salinity are estimated at US$ 27 billion for the world and US$ 1.2 billion for India having 6.74 million salt-affected soils. It is projected that 13 million ha area in irrigation commands of India will be affected by waterlogging and soil salinity by 2025 and over 20 million areas by 2050 due to climate change and enforced increasing use of saline/alkali groundwater in several northwestern and southern states.

Preservation and restoring the productivity of irrigated agriculture without environmental degradation is a challenging task and demands regional planning and management perspectives. Though a number of preventive on-farm and project-level water management measures are recommended, improved drainage conditions become inevitable once irrigation-induced salinity develops over large areas. Besides surface drainage, engineering technologies like subsurface drainage (SSD) and tubewell drainage (and associated variants) and biological approaches like biodrainage through high-transpiring trees have been applied extensively for control and amelioration of waterlogging and soil salinity in different countries including India. While watertable control in fresh groundwater regions is commonly achieved by tubewell pumping, horizontal pipe drainage is almost mandatory in waterlogged and saline groundwater regions. There are, however, no clear guidelines for the selection of particular drainage methods appropriate for any affected area with specific hydrogeological characteristics.

Basic features of SSD and related interceptor and mole drains and vertical and biodrainage approaches for management of waterlogged saline-irrigated lands have been presented along with preliminary guidelines adopted in the past for selection of SSD or vertical drainage system. A major part includes critical review of SSD, vertical and biodrainage projects and related variant technologies developed and evaluated for different agroecological regions of India. The presented variants of vertical drainage system include different types of skimming and recharge structures used for selective abstraction of fresh water floating in a thin layer over native saline groundwater and for disposal of excess flood water from agricultural fields, respectively.

Finally, a case study is presented for the identification of critical and potentially critical waterlogged saline areas of Haryana, most suitable for reclamation through SSD, vertical or biodrainage measures. Selection of sites for appropriate drainage approaches is based on a watertable depth (WTD) and groundwater salinity (EC_{gw}) linked criterion: SSD (WT~ 0–1.5 m; EC_{gw} >2 dS m^{-1}), tubewell drainage (WTD ~ 0–3 m; EC_{gw}, 0–2 dS m^{-1}) and biodrainage (WTD ~ 0–1.5 m; EC_{gw} 0–2 dS m^{-1}).

Land drainage deserves more recognition than it has received so far in India. It is important to recognize significant benefits of land drainage on crop yields and sustainability of irrigated agriculture. Following salient observations and recommendations are synthesized on the effectiveness and scope of SSD, vertical drainage and biodrainage approaches for irrigated lands of India:

(a) *Subsurface Drainage (SSD) Technology*

1. SSD is a technically feasible, cost-effective and socially acceptable technology for reclamation of irrigated waterlogged saline lands. The technology, introduced systematically by CSSRI during early 1980s in Haryana, has

resulted in implementation of mechanically installed large SSD projects in about 62,000 ha area in different states in India.

2. SSD can result in 40–50% increase in cropping intensity, 50–150% increase in yields of different crops and 2–3-fold increase in farmers' income in 2–4 years from hitherto non−/less-productive lands. The technology can result in a benefit-cost ratio of 1.5, IRR of 20% and employment generation of 128 man-days per ha every year.
3. The estimated cost of SSD systems for Haryana and other northwestern states (60 m drain spacing, 1.5–2.0 m drain depth and pumped outlet) is INR 79000 ha^{-1}. Corresponding cost at 30 m spacing, 0.8–1.2 m depth and a gravity outlet for heavy soils in Maharashtra, Karnataka, Gujarat and other *Vertisol* regions, is recommended at INR 1,11,500 ha^{-1}.
4. The operational cost of SSD system in NW states is mainly due to pumping of the drainage effluent. After 1–2 years of operation of the drainage system, the quality of drainage effluent improves to a level that it can be reused for irrigation.
5. High cost, environmental issues relating to disposal of saline drainage effluent and continuous pumping requirement during post-drainage phase are some of the deterrents to long-term success of this technology. Involvement of farmers, sharing of construction and operating cost and government subsidy are other vital aspects.
6. Extensive waterlogged saline areas in alluvial regions of central Haryana, South-west Punjab and Northern Rajasthan urgently need SSD and other technologies like vertical drainage, biodrainage, salt-tolerant crop varieties, micro-irrigation in horticulture crops and saline fisheries.
7. These states must prepare regional master plans with clearly identified areas for implementation of different amelioration technologies and related fund requirement.
8. The methodology proposed in this chapter for identification of areas for priority implementation of SSD, biodrainage and vertical drainage projects in Haryana may be refined further to incorporate environmental aspects for disposal of saline drainage effluent.
9. The concerned states must also procure additional drainage machinery and develop outsourcing mechanisms in PPP modes to enhance the pace of implementation of SSD projects.
10. Regional salinity management and planning requires accelerated application of monitoring systems based on EM38, GPS, GIS, remote sensing and mathematical models.

(b) *Vertical Drainage System*

As a broad principle, vertical drainage systems cannot be used to control waterlogging if groundwater is saline and salinity increases with depth. However, skimming structures, based on the principles of vertical drainage, have proved successful in a limited way to pump out fresh water floating in thin layer over saline groundwater in coastal and inland irrigated areas.

1. A series of single tubewell projects have been successfully implemented to lower watertable in vicinity of canal distributaries in Haryana and Rajasthan during the 1990s. These projects have not been implemented in later years because of ambiguity and lack of guidelines for selection of appropriate drainage method for waterlogged areas.
2. Multiple strainer wells, reported successful to skim fresh water close to canals/distributaries in Punjab in India and in Indus Plains of Pakistan, have not been replicated at other locations in India because of lack of guidelines for selection of appropriate sites for such systems.
3. Radial collector well-type structures have considerable scope in coastal sandy soils for skimming of fresh water from thin sandy zones. The cost of the system can be considerably reduced by standardizing the techniques for horizontal drilling of drains in sandy soil.
4. Pilot projects on scavenger wells, tested successfully to pump simultaneously fresh and saline water from two groundwater quality depth zones in lower Indus Basin of Pakistan and other countries, also need to be evaluated under well-defined hydrogeological conditions in India.
5. Individual farmer-based recharge wells are effective to work as a local drainage system to save crops from submergence due to heavy rains in low-lying sections of inland areas, besides augmenting groundwater and improve quality.
6. Incorporation of small and less costly recharge filters in the abandoned dug-wells can contribute to significantly enhance groundwater recharge and consequent reduction in flood damage to crops. Issues relating to effective designs of recharge filters and quality of recharging water need to be taken care for implementing recharge projects over large areas.

(c) *Biodrainage*

1. Biodrainage is a biological approach to prevent development of salinity and waterlogging in canal commands. It is effective only when soil salinization due to watertable rise has not reached a serious level. Moreover, in bowl-shaped watersheds where drainage is not feasible, biodrainage helps in lowering down of watertable, and farmers may cultivate their fields particularly after rainy season.
2. *Eucalyptus tereticornis* is the most common species for lowering of watertable and seepage control from canals in waterlogged areas. The paired row strip plantations of this species, on field boundaries at plant density of 300 plants ha^{-1}, resulted in lowering of shallow groundwater by 0.85 m in 3 years and by ~ 2 m after 5 years in shallow groundwater regions of Haryana. Whenever crop cultivation is not feasible, the block plantations or trees in wider rows (row-to-row distance 4–5 m) in agroforestry mode may be grown, which will help in lowering down of watertable at faster rate, and agroforestry crops can be cultivated in interspaces successfully at least during initial 3 years of plantations (Dagar et al. 2016).
3. For command areas, planting of 100 m or wider belts of high water-demanding trees such as *Eucalyptus*, *Populus*, *Leucaena*, *Acacia* and

Bambusa along the canal and interspace grasses have been recommended for controlling the waterlogging problem. Research efforts are needed to find out exact size of belt required to be raised along with canals for effective control of seepage depending upon nature of soil of the canal area and species to be grown.

4. A major factor determining the sustainability of biodrainage projects is attainment of long-term salt balance in the soil profile in shallow saline groundwater regions. These studies need to be conducted further.

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19 Reclamation of Salt-affected Soils in the Drylands of Ethiopia: A Review

Hintsa Muruts, Hailay Haileselassie, and Yohannes Desta

Abstract

The need to feed the growing population of Ethiopia could be addressed by changing salt-affected soils into productive land. This review begins by establishing why and how salt-affected soils, mainly saline soils, are created in the drylands of Ethiopia. The review presents experiences in reclaiming salt-affected dryland soils of Ethiopia and shows future research priorities to augment and sustain the agricultural productivity of these soils. It also considers knowledge on the benefits that woody plants provide in sustainable remedies for salt-affected soils by their use in agroforestry systems/practices. Finally, the review discusses the considerable practical work that remains to be done, as well as the importance of collaboration of multidisciplinary teams of workers to properly reclaim and manage soils, which are affecting farmers most severely in the drylands of Ethiopia. Salt-affected soils in Ethiopia are predominantly found in the Great Rift Valley plain, including the Awash River Basin and Omo River Basin, Lakes Turkana and Chew Bahir, the southern Rift Valley, areas near Ziway and Shala, and around the Abaya lakes.

Keywords

Agroforestry · Reclamation · Salt-affected soils · Dryland

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19.1 Introduction

Ethiopia has a very vast area that can be classified as a dryland. It covers an area of 75 million hectares, which is 66% of the country's total area (Demel undated). These large areas of dryland are associated with recurrent problems of salinity. Debela (2017) has noted that salinity and alkalinity problems are more common in arid and semiarid areas of Ethiopia. In 1988, Abrol et al. (1988a) reported that the area of salt-affected soil in Ethiopia was 10,608,000 ha of saline soil plus 425,000 ha of sodic soil. The highest portion of salt-affected soils in Ethiopia are found in the lowland areas of Afar, Afar, Somali, and Oromia. Salt-affected soils are also found in the Great Rift Valley, including the Awash River Basin in the northern Rift Valley, the Omo River Basin in the southern Rift Valley, Lakes Turkana and Chew Bahir, and areas in and around Ziway, Shala, and the Abaya lakes. High spots of saline soils are also common in the drylands of Ethiopia, mainly in small perennial or seasonal river valleys (Abebe and Zeit 2015; Tessema 2011; Girma and Endale 1996; Heluf 1987).

The problems of salt-affected soils are long-standing ones, but their magnitude and intensity have been increasing at alarming rates because of poor water quality, poor on-farm water management practices, and lack of adequate drainage facilities at irrigation sites. It is estimated that Ethiopia has an area of 44 million ha (36% of the total land area) that is potentially susceptible to salinity problems, and an area of 11 million ha has already been affected by different levels of salinity. For example, Zewdu et al. (2016) found that the coverage of moderately and strongly saline areas increased at an annual rate of 4.1–5.5% within a short period from 1984 to 2010 at the Sego Irrigation Farm in southern Ethiopia. Despite the widespread occurrence of salt-affected soils in Ethiopia, the scientific information available so far is scanty. Thus, this review will prompt researchers to conduct further detailed study on key reclamation of these soils. Review of research findings on reclamation of salt-affected soils is an important topic, particularly for agricultural management and for developing countries, including Ethiopia, where agriculture is the backbone of the economy.

19.2 Development of Dryland Salinity

19.2.1 Occurrence of Salinity in Dryland Areas

When groundwater rises up to the surface of the landscape in dryland, salt will accumulate, as there will be a water imbalance. Accordingly, soil salinity will develop. Similarly, the levels of groundwater increase when the rate of recharge is greater than the rate of discharge (water leaving the system). The occurrence of saline soils is a natural phenomenon in Ethiopia, where water tables are near the soil surface. Tessema (2011) explained that soil salinity and poor soil drainage have occurred as a result of poor soil condition and use of irrigation systems at the Fursa River diversion irrigation project (in Ada'Ar Woreda [district], Afar Regional State, Northeastern Ethiopia). Other research conducted by Bekele et al. (2012) found that

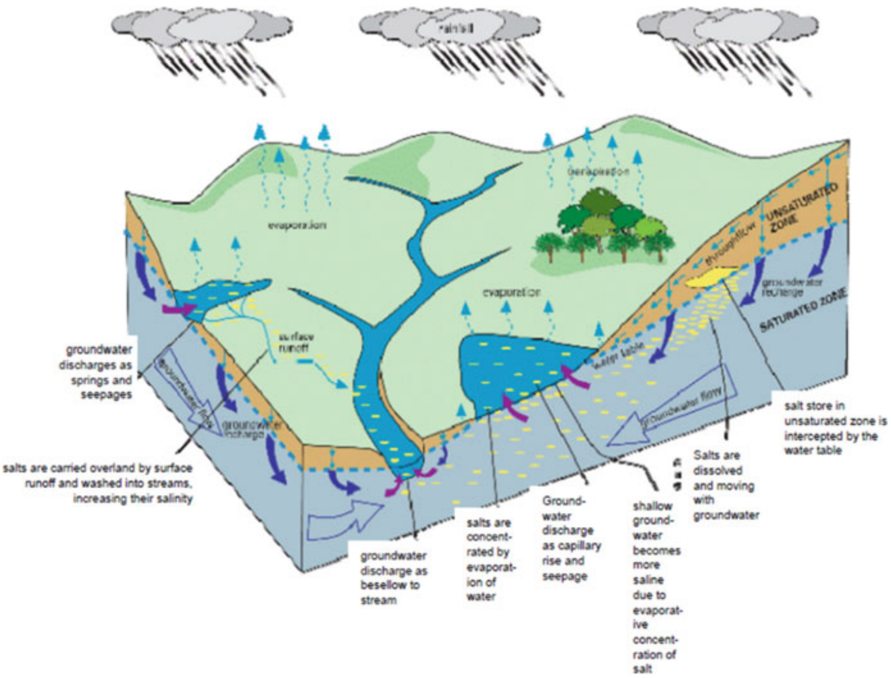

Fig. 19.1 Hydrological cycle and salinity processes

the impacts of irrigation on soil salinity and crop production in the Gergera watershed (in Atsbi-Wonberta, Tigray, Northern Ethiopia) have shown a potential risk of soil sodification as a result of the use of surface water for irrigation, and he suggested adopting alternative water and crop management practices for sustaining crop productivity. Moreover, salt-affected soils are also created as a result of application of low-quality irrigation water.

In Ethiopia the soils found in the Central Rift Valley are naturally sodic in the subsurface horizons, and the use of marginal-quality groundwater for irrigation has aggravated the formation of salinity. The main elements of the hydrological cycle are presented in Fig. 19.1, which shows the water cycle involved in the salinity process (CALM 1993).

Precipitation is generally considered the starting point of the hydrological cycle. Precipitation can occur in the form of either rainfall or snow. Rain may be intercepted by vegetation or collected in land surface depressions, may infiltrate the soil, or may run over the land surface into streams. Hence, the infiltrating water may be stored in the soil as soil moisture or may be percolated and join the groundwater. When the groundwater level is very shallow, the groundwater will rise in the form of capillaries that carry soluble salts and leave them on the surface of the soil. This creates salts that clog the soil pores and finally result in a salinity problem.

19.2.2 Factors Contributing to Dryland Salinity

Dryland salinity (or no-irrigation salinity) can occur as a result of lack of replacement and loss of natural vegetation and growing of crops and pastures that reach the groundwater system at different depths. Groundwater rises near to the top surface in low-lying areas or on the break of slopes (this is called discharge). Groundwater can also flow directly into streams. Groundwater carries dissolved salts from the underlying soil and bedrock (NSW Department of Land and Water Conservation 2000).

Other factors that cause salinity hazards include climate, hydrogeology, catchment shape, and land use (Figs. 19.2 and 19.3). Accordingly, dryland salinity can be estimated by assessing the main factors affecting salinity, such as the potential time frame, the severity, and the size of the area.

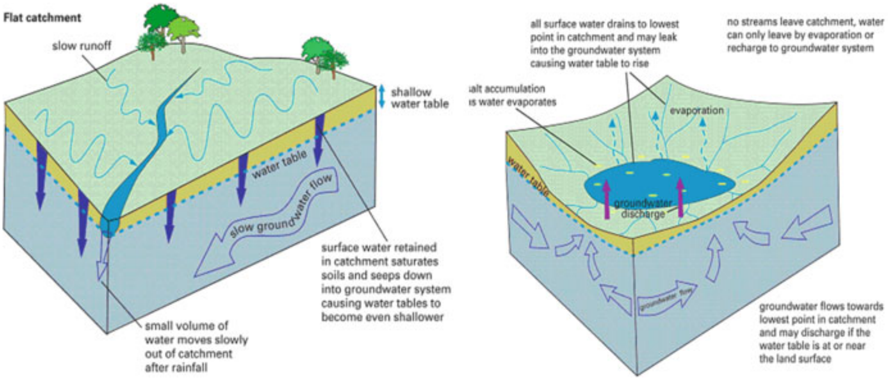

Fig. 19.2 Groundwater flow (*left*) and evaporation (*right*) in developing soil salinity

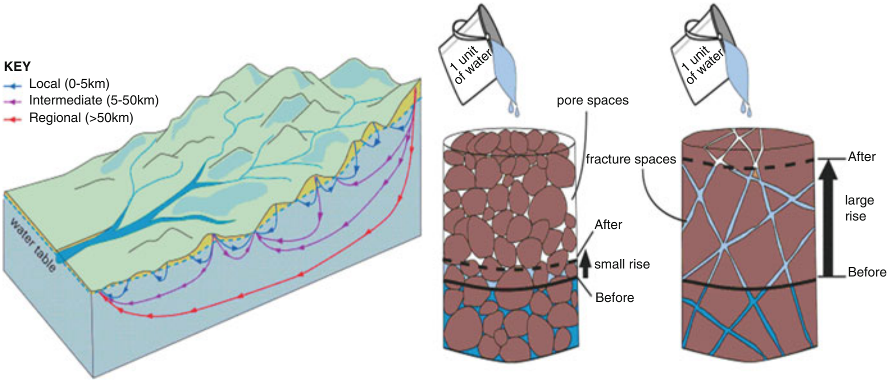

Fig. 19.3 Groundwater table (*left*) and soil pores in the substrate (*right*)

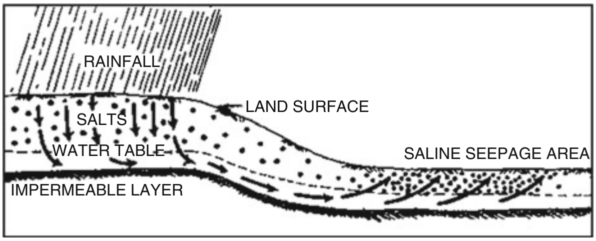

Fig. 19.4 Model of salinity formation

From Figs. 19.2 and 19.3, it can be seen that when the rise of groundwater comes close (<5 m) to the topsoil surface, as a result of capillary rise, soil salinization and waterlogging occur. Similarly, increased hydraulic gradients (or slope differences in the water level) in streams, lakes, and dams as a result of groundwater can lead to greater movement of saline groundwater into these surface water resources (Jolly et al. 2000).

Figure 19.4 shows a model of saline soil formation, illustrating how different factors affect and contribute to different levels of salinity (Abrol et al. 1988b).

The development of saline seeps involves recharge and discharge areas in the field. In areas where recharge is high, the amount of water is in excess of the retention capacity of the root zone, and the water percolates beyond the root zone and joins the groundwater, so the discharge area will be increased. The groundwater flow, for the most part, is lateral and downslope, and exists most commonly over a shallow and less permeable layer. The groundwater joining the discharge area carries dissolved salts from the soil. As the groundwater rises to the soil surface, it creates a seep. When water evaporates from the seepage area, it leaves salts and accumulates in the surface layer of the soil.

Degol et al. (2010) noted that the Gerjalle area in northern Ethiopia was densely forested and there was no swampy indication. Instead, there was a shortage of water for both human and livestock consumption. According to information obtained from interviews with local people, the water table started to rise after farmers started to cut down and destroy the dense forest. This indicated that in the past, the native woodland forests were able to keep the water table at a lower depth and could keep the salt in balance. Therefore, deforestation may be another possible reason for water table rise and salt build-up.

19.3 Reclamation of Saline Soils in the Drylands of Ethiopia

There have been experiences of saline soil reclamation through leaching, leaching plus artificial drainage, and managed land shaping to reduce salt accumulation in the drylands of Ethiopia.

19.3.1 Leaching

Intermittent flooding is commonly used in initial leaching. Preference is given to flooding of fields bordered by drains and divided into small basins (see Box 19.1). For most surface irrigation systems in Ethiopia, surface flushing (flooding, puddling, draining) prior to normal downward leaching may accelerate and improve the leaching process.

Box 19.1

According to Fentaw and Girma (1996), a leaching trial was conducted in the Melka Sedi area, where a subsurface drainage system had already been installed. The results of the leaching experiment revealed that the salinity level of the upper soil horizon was drastically reduced by the leaching practices in comparison with the initial salinity level. The salinity of the 0- to 30-cm soil depth was drastically reduced after irrigation water applications of 30 and 40 cm depth (in the first and second applications, respectively), and the salinity reduction gradually continued until the end of the experiment. In effect, the soil salinity increased in the lower profile (30–120 cm) with the irrigation water applications of 30 and 40 cm depth in continuous ponding treatments. This is because the applied irrigation water was sufficient to transport the soluble salts from the upper soil profile and deposit them in the lower soil depths. In general, as the cumulative leaching increased, the salinity level was reduced from the predetermined soil profile in the continuous ponding treatments. Thus, keeping salt-affected soils under continuous wetting contributes to salinity removal from the root zone. At the 30- to 60-cm soil depth, the salinity level showed an increasing trend after leaching water applications of 60 and 40 cm in intermittent ponding—i.e., 210 and 280 cm cumulative water depths, respectively. Further, application of 90 and 80 cm of leaching water resulted in salinity build-up at lower soil depths (60–120 cm) with intermittent treatments. This could possibly have been a result of transport of soluble salts from the surface layers to the lower profiles. Application of relatively deep leaching water is sufficient to reduce existing and incoming soluble salts at lower soil depths with intermittent ponding treatments.

19.3.2 Leaching Plus Artificial Drainage

When shallow water tables limit the use of leaching, artificial drainage may be needed as an alternative option to reclaim salt-affected soils. Drainage ditches in fields below the water table level can be used to channel away drainage water and remove salt (see Box 19.2). Drainage tiles or plastic drainpipes can be also used for leaching out salts.

Box 19.2

Subsurface drainage systems were installed, occupying some 25 ha of alluvial soils, at the Melka Sedi State Farm as a pilot drainage scheme to verify the effectiveness of subsurface drainage systems in controlling soil salinity levels for sustainable crop production. The subsurface drainage system in the Melka Sedi pilot drainage scheme was singular, i.e., each pipe drain line had an outlet into an open ditch. Corrugated polyvinyl chloride (PVC) pipes with a slot size of 1 mm (except for Pilot test piping with 2-mm slots) were used as subsurface drains. A pipe diameter of 80 mm was used for 75-m drain spacing and a pipe diameter of 60 mm was used for 40- and 20-m drain spacing. The soil salinity was reduced considerably after the installation, except at a lower depth of the soil profile with the 20-m drain spacing. The salinity build-up was due to backflow of drain water from the collector drain to the field (Fentaw 1996).

When artificial drainage systems are being used, care must be taken in disposing of the drainage water. For the duration of the disposal, this may incur significant costs, which may be not viable for smallholding farmers in Ethiopia. The advantage of artificial drainage is that it provides low-salinity irrigation water to remove salts completely from the soil. However, artificial drainage systems will work only where there is a saturated condition in the soil. Moreover, if the water is to be drained easily, the soil should be well saturated. Leaching will begin when the drainage appears adequate.

19.3.3 Managed Land Shaping to Reduce Salt Accumulation

Leaching below the root zone can remove salt from the primary root zone with certain crop-bedding and surface irrigation systems. The aim is to ensure that zones of salt accumulation stay free from germinating seeds and plant roots. When there is no uniform distribution of water, salts will accumulate in some areas, where germinating seeds and seedling plants will experience growth reduction and finally dry out and die. In dryland areas, proper planting beds minimize salt accumulation around the seed. In flat-topped beds, the salt initially present in the intake soil is transported in the wetting front and accumulates in a thin layer along the top of the bed and under the bed center where opposing wetting fronts meet.

19.3.4 Other Reclamation Options

Experiences of reclamation in Ethiopia are described in Boxes 19.3, 19.4, 19.5, and 19.6.

Box 19.3

The Amibara irrigation scheme in Ethiopia has encountered problems of salinization and rising water tables. The soils in the farm area were normally nonsaline, and the groundwater table had been below 10 meters three to four decades earlier (Halcrow 1983). Nevertheless, subsequent unsustainable management of irrigation water and lack of a complementary drainage system caused waterlogging, salinization of the whole productive area, and considerable losses in productivity. In an interview with *The Ethiopia Herald*, Bethel Nekir, the Saline Soils and Drainage Researcher and National Coordinator, said that because of the area becoming saline, the productivity and the variety of crops growing at the site were decreasing, and the existence of high temperature and mismanaged irrigation farming for over four decades had been threatening farmers' livelihoods. In his interview with *The Ethiopia Herald*, Ashenafi Werku, the center's Salty Soils Improvement Program Researcher, explained that they had identified three kinds of fodder that could be successfully grown, which have their own varieties. These species of fodder reduce the amount of salt in the soil while being able to grow well in salty soils (Katema 2018).

Box 19.4

Studies done by the Werer Agricultural Research Center in Ethiopia in 2011–2014 showed promising results in terms of salinity tolerance, biomass yield, and ameliorative effects for four forage crop species (*Cenchrus* sp., *Panicum antidotale*, Sudan grass (*Sorghum sudanense*), and *Chloris gayana*) and three legume species (*Desmodium triflorum*, *Sesbania sesban*, and *Medicago sativa* (alfalfa)). The salt stress levels to which *Cenchrus* sp., *P. antidotale*, Sudan grass, and *C. gayana* were subjected had mean electrical conductivity (ECe) values of 8.2, 10.4, 12.7, and 17.9 dS m^{-1}, respectively. The biomass yields obtained under saline soil conditions were closely comparable to those obtained under normal soil conditions (EIAR 2015).

Box 19.5

Barley (*Hordeum vulgare*), sorghum, wheat, mustard, and oilseeds (safflower and sunflower) are among the economically important crops with genetic diversity for better adaptation under saline soil conditions. Barley is among the cereal crops widely grown in the highland areas of Ethiopia, and its cultivation is about to be expanded to midaltitude areas as well. Although barley is among the commonly grown cereal crops and has been well described for its potential ability to tolerate stress induced by salinity, its introduction and potential use in marginal environments is not common in the country. However, farmers in the Ziway Dugda area in Ethiopia have previously grown barley instead of maize and other horticultural crops when their soil was becoming more salinized.

Box 19.6

In Ethiopia, research is in progress, with the major aim of collecting and evaluating the potential of local halophytes for wide economic use in arid and semiarid regions in view of the progressive shortage of freshwater resources and expanding soil salinization. Collection of halophytes during 2016 from a farm area where soil salinity caused only limited effects in Middle Awash in Ethiopia indicated wide distribution of halophyte species that are of interest because of the potential for different economic uses of these species under environmental stress conditions (Qureshi et al. 2018).

19.4 Conclusion and Implications

Dryland areas with low to moderate salinity levels can be reclaimed by introducing improved irrigation and crop management practices. A biological approach is one of the easiest approaches for reclamation and management of salt-affected soil, especially for smallholding farmers in Ethiopia who do not have the resources to apply costlier corrective measures. Careful selection of salt-tolerant crops, including underexplored halophytes of economic importance and/or woody species that can grow satisfactorily under moderately to highly saline soil conditions, are also proposed to reclaim salt-affected soils.

All major irrigation schemes in Ethiopia face problems of soil salinity, which can be partly tackled by planting fast-growing trees. However, the potential of many multipurpose tree species, including salt bush (*Atriplex* spp.), to reduce salinity in the drylands has not yet been adequately evaluated and appreciated. Moreover, researchers could focus on identification of a number of indigenous agroforestry systems and practices that are profitable and viable in a variety of salt-affected environments. Finally, it is concluded that much practical work remains to be done, and participation of multidisciplinary teams of scientists is essential to properly reclaim and manage saline soils, which are expected to affect farmers most severely in the drylands of Ethiopia.

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Reviving the Productivity of Salt-affected Lands: Technological Options, Constraints and Research Needs

20

P. C. Sharma and Anshuman Singh

Abstract

Salinization of productive croplands and fresh water is essentially a threefold setback, reducing the soil productivity, necessitating unwarranted expenditure on reclamation and causing (often irreparable) decline in vital soil functions and environmental services. In spite of global efforts, unabated salinization continues to swallow prime lands in several irrigated and dryland regions with estimates suggesting that nearly half of the global irrigated lands could become salt impaired by 2050. A suit of interventions including soil and water amendments, agronomic manipulations, salt-tolerant cultivars and improved irrigation and drainage management are suggested for overcoming various constraints in salt-affected soils. Of late, climate variability-induced stresses like high temperature, erratic rainfall, freshwater scarcity and seawater intrusion in coastal areas are not only imposing additional constraints on soil reclamation but are also hastening secondary salinization. This article reviews the progress in agricultural salinity management through conventional and emerging technologies, identifies major barriers in their use and suggests some future research needs.

Keywords

Alternative amendments · Food production · Prime lands · Reclaimed soils · Salinity · Salt-tolerant cultivars · Secondary salinity

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20.1 Introduction

Healthy soils and fresh water are essential to fulfil the diverse needs of the human society. In addition to producing food, fodder, fibre and fuel, soils also act as strong carbon sinks to lessen the impacts of global warming and possess a tremendous diversity of flora and fauna critical to many ecosystem services and functions. Notwithstanding the crucial roles they continue to play, global soil and water resources are facing constant threats of pollution and degradation. Salinization along with erosion, compaction, nutrient depletion and acidification is recognized as a key driver of soil and water degradation (FAO and ITPS 2015). Evidence is mounting that growing global food demands, dietary transition and rising consumption of biofuels are placing an unprecedented demand on overstretched land and water resources. Global population, projected to cross 9.0 billion by 2050, has necessitated quantum improvements in food production. Current global demand for food and feed is predicted to increase by ~70% by the middle of this century. An additional 1 billion tonnes of cereals alone will be required to sustain the rising food demands. Increase in per capita incomes and the changing lifestyles are also fuelling the increased consumption of fruits, vegetables, milk, egg and meat, especially in developing countries (FAO 2009). Nutritional transition from cereal-centric diets to nutrient- and energy-rich food implies that production of these commodities must keep pace with the current and projected demands. However, prospects of setting aside a part of land under food staples for other commodities remain virtually impossible; extending their cultivation to the unused and abandoned lands seems to be the only feasible option for meeting their increased demands. There is immense possibility of utilizing large tracts of barren and uncultivated land for crop production provided appropriate measures are in place to overcome constraints impinging their use (FAO 2011).

Despite a pressing need to augment the global food production, yield increases even in major food staples (e.g. rice, wheat and maize) remain far below the projected levels (Ray et al. 2013). Currently, agricultural activities account for nearly one-third of the world's land surface excluding Greenland and Antarctica. Because most of the arable lands have been brought under cultivation, there is an increasing attention on tapping the productivity of marginal lands for addressing the ever-rising food requirements (UNCCD 2017). Unabated population growth is increasingly making productive agricultural land a scarce resource: global average per capita land availability declined from ~0.75 ha person^{-1} in 1900 to ~0.35 ha person^{-1} in 1990. Thanks to the continual refinements in agro-techniques, average yields have consistently increased in many crops. Nonetheless, growth in the total output has not been sufficient to meet the existing food needs. Consequently, new options are increasingly being explored to increase the crop production (Ramankutty et al. 2002). Although agricultural intensification continues to be seen with optimism for breaking the yield barriers, intensively managed croplands tend to show the signs of physical and chemical degradation in the long run (Lemaire et al. 2014). Despite substantial improvements in global food production in the last five decades, undernourishment and micronutrient deficiencies still remain a significant concern in many parts of the world. Providing adequate nutrition to the world population without further harming the environment continues to be challenge to the researchers and policymakers (Ramankutty et al. 2018).

Based on their capacity to reach potentially attainable yields in a range of crops, croplands are classified into prime, good and marginal categories. While a prime land can produce up to 80% of potentially attainable yields, good and marginal lands would produce only 40–80% and <40% of the potential yields, respectively. Prime (28%) and good quality (53%) lands together constitute 81% of the global cropped area (FAO 2011). Marginal lands suffer from different climatic and soil constraints, making them less productive or, sometimes, entirely unsuitable for food crops. Both natural (e.g. extreme aridity) and anthropogenic (e.g. intensive input application and excess irrigation) factors often set in motion a series of degradation processes, diminishing soil health to the extent that restoration measures become essential to ensure stable crop yields (Lewis and Kelly 2014). Adverse climatic conditions and inappropriate anthropogenic interventions operating in tandem may inflict very serious damages over time, a fact perhaps best evidenced by relentless irrigation-induced secondary salinization in several arid regions of the world. There is evidence that in contrast to most of the field crops which perform poorly in marginal areas, there are ample prospects for growing other crops under such situations, albeit with the aid of improved management practices. Furthermore, many cereal and pulse crops requiring lesser water and other inputs and displaying certain degree of tolerance to abiotic stresses like drought and salinity can also be grown in marginal lands successfully. Salt-affected soils (SAS), an important example of marginal land, face a range of constraints imposed by the presence of excess soluble salts and/or exchangeable sodium and other associated problems like waterlogging and drought. Salt-affected soils have been reported from about 100 countries occupying nearly 1 billion ha area (FAO and ITPS 2015).

It is suggested that at least 20% of global irrigated lands suffer from salinity and/or sodicity problems to varying extents with relentless salinization likely to impair nearly half of the global arable lands by 2050. In addition to direct adverse effects on soil properties and crop yields, salt accumulation also renders freshwater aquifers saline. When water movement into aquifers exceeds the outflows, rise in water table brings dissolved salts to the root zone and the surface layers, negatively affecting soil properties (UNCCD 2017). Adverse factors like high aridity, salinity and freshwater shortages are also severe impediments to the productive utilization of a sizeable arable area in drylands (Pannell and Ewing 2006). Rising global population and the attendant increase in urbanization are predicted to grab nearly 2.4% of the global croplands by 2030 with Asia and Africa projected to be hit hard. If this prediction comes true, total global crop production will decrease by about 4% compared to the year 2000 (d'Amour et al. 2017). Irrigated lands, which currently provide a little over 40% of the global food, are facing an unprecedented pressure imposed by the diminishing fresh water. Pollution of surface and groundwater resources caused by domestic and industrial effluents coupled with secondary salinization is wreaking havoc in many areas. Globally, about 70% of the fresh water is used in agricultural production. In developing economies like India, as much as 90% of the total available water is used for this purpose, implying an immediate need for curtailing the freshwater use by improving crop water use efficiency and exploiting nonconventional water resources in irrigation. In many areas, cultivation of drought- and salt-tolerant crops or those capable of enduring the twin stresses of waterlogging and salinity may be the only viable option for obtaining acceptable crop yields (Sharma and Singh 2017).

Conventionally, salt-affected soils (SAS) are distinguished from the normal ones on the basis of soil saturation paste extract electrical conductivity (EC_e), pH (pH_s) and exchangeable sodium percentage (ESP). Based on the values of these parameters, SAS are grouped into saline, sodic and saline-sodic categories. However, there are no universally accepted benchmarks, and the accepted values of these soil properties to classify the SAS can vary from country to country. For example, while in India, SAS are classified into saline ($EC_e \geq 4$ dS m^{-1}, $pH_s < 8.2$, ESP < 15) and sodic ($EC_e < 4$ dS m^{-1}, $pH_s > 8.2$, ESP >15) categories, in the United States, they are categorized into saline ($EC_e \geq 4$ dS m^{-1}, $pH_s < 8.5$, ESP <15), sodic ($EC_e < 4$ dS m^{-1}, $pH_s > 8.5$, ESP >15) and saline-sodic ($EC_e \geq 4$ dS m^{-1}, $pH_s > 8.5$, ESP > 15) groups. Again, in Australia, soils with ESP values of 6–15 are designated sodic. Salt-affected soils are also frequently underlain with saline and alkali (sodic) waters, further increasing the salt stress in crops and imposing the difficulties in soil reclamation. Salinity hazard of irrigation water can be assessed by measuring the total dissolved salts, expressed as dS m^{-1} (EC), mg L^{-1} (ppm) or me L^{-1}. Similarly, sodium adsorption ratio (SAR), residual sodium carbonate (RSC) and adjusted SAR are estimated to evaluate the sodicity hazard. In India, for example, salty irrigation waters are classified into good ($EC_{iw} < 2$ dS m^{-1} and SAR < 10 mmol L^{-1}), saline ($EC_{iw} > 2$ and SAR < 10), high-SAR saline ($EC_{iw} > 4.0$ and SAR > 10) and alkali (EC_{iw} variable; SAR variable and RSC > 2.5 meq L^{-1}) categories. Prolonged use of such waters may cause irreversible deterioration in soil health, especially in the absence of appropriate soi1, water and crop management practices (Minhas and Tyagi 1998).

In this paper, different amendment-, engineering- and plant-based solutions for reclaiming and manging the salt-affected soils have been presented. Relative merits and demerits of such interventions are analysed. Constraints being imposed by the strong climatic variability, freshwater depletion and rising amendment costs have been delineated to suggest the future research needs.

20.2 Technological Options

It is beyond any doubt that reclamation and management of salt-affected soils and waters is of paramount significance in improving food productivity and in easing the pressure on shrinking prime lands and fresh water. Available evidence suggests that even modest improvements in the agricultural productivity of saline and sodic lands will contribute greatly to reducing poverty and hunger in many areas of the world. Different agronomic and engineering options for agricultural salinity management and the constraints impinging their widespread use are presented under the following heads.

20.2.1 Chemical and Organic Amendments

20.2.1.1 Mined Gypsum

Although a range of chemicals including soluble calcium salts like gypsum, acids or acid-forming substances like sulphuric acid and pyrite and sparingly soluble calcium salts such as limestone have been suggested for removing the excess Na from soil exchange sites, gypsum ($CaSO_4.2H_2O$) has emerged as the most popular amendment due to its low cost, easy availability and ease of application than other chemicals. Certain amendments like $CaCl_2$ are very soluble, producing a leaching solution of high electrolyte concentration which increases water intake and thus higher reclamation efficiency. However, they may be cost prohibitive unless available as a waste product. Similarly, sulphuric acid is a very efficient ameliorant for sodic calcareous soils but requires special handling and application equipment rendering it less appealing for soil reclamation (Prather et al. 1978). In addition to major use as soil ameliorant, gypsum has long been used as a soil conditioner and as a source of nutrients (Ca and S) for crop plants. Traditionally, the total quantity of gypsum to be applied is determined mainly on the basis of amount of Ca required to decrease the soil ESP below a specific level ignoring other factors like presence of other sources of Ca in the soil solution. Routine computations of gypsum requirement (GR) – the amount of gypsum required to reclaim a sodic soil – neglect the role of calcium carbonate (calcite) in the exchange process. Notwithstanding the popular perception that calcite is insoluble, certain factors like high CO_2 tend to hasten its dissolution that is also influenced by irrigation water alkalinity and Ca content (Suarez 2001). A similar situation prevails in saline-sodic soils of the Indo-Gangetic Plains and elsewhere where sodium carbonate is often present in excess amounts. When added to such soils, Ca in the gypsum reacts with soluble carbonates to form relatively insoluble $CaCO_3$, and the subsequent decrease in Ca content of gypsum solution results in the overestimation of GR (Abrol et al. 1975). Imprecise GR determinations lead to the excess amendment use, inflating the reclamation costs and resulting in leaching of salts to the groundwater. Given the equilibrium between Na and Ca, complete exchange reactions seldom occur, causing Ca movements from root zone through leaching. It is due to this reason that quantitative models capable of integrating such factors are needed to precisely determine the GR (Šimůnek and Suarez 1997). Gypsum requirement also depends on the desired depth of reclamation. The reclamation efficiency of gypsum depends on its dissolution properties that in turn are influenced by the composition of the soil solution, surface area of gypsum fragments and the soil water velocity during leaching. Decrease in soil ESP with depth would be lower at higher soil water velocity. In general, the slower the soil water velocity, the higher the efficiency of replacing Na^+ by Ca^{2+} (Keren and O'Connor 1982).

In countries like India, gypsum and other amendments (e.g. pyrite) are generally broadcast on the surface and then mixed into soil by ploughing. Surface application is preferred over subsurface application because deeper mixing results in the dilution of gypsum and thus poor reclamation efficiency. Again, when applied at some depth, a considerable proportion of gypsum is likely to be wasted in neutralizing the soluble carbonates throughout 30 cm soil profile, while ESP may be high in the upper 15 cm or so. Surface application hastens Na^+ displacement from the exchange sites resulting in higher hydraulic conductivity and the associated benefits (Abrol et al. 1988). Notwithstanding this argument, some subsequent investigations revealed that surface treatment though effective in promoting crop growth does not lead to complete amelioration as evidenced by only partial improvements in soil properties (Sharma and Singh 1993). Such surface (gypsum)-treated soils have accordingly been designated as 'partially reclaimed' or 'semi-reclaimed'. Partial reclamation can be one of the reasons for the poor productivity of such reclaimed lands necessitating investigations to see whether reclamation up to 30 cm depth gives better and long-lasting results or not. In addition to soil application, gypsum has also been widely used for neutralizing high RSC irrigation waters by passing the sodic groundwater through a brick-cement chamber containing gypsum clods. Sodic waters flowing through the gypsum bag/clods become saturated with Ca^{2+} (3–5 meq L^{-1}) and thus far less toxic than original Na^+ laden water (Minhas and Tyagi 1998). Thus, gypsum treatment of water may be more efficient than soil application; while sodicity may remain high even when full amount of gypsum is applied as a single basal dose to the soil, waters passing through gypsum chamber virtually become neutral and thus greatly reduced or no risks of soil sodification. However, construction of gypsum beds and repeated gypsum use may entail additional expenses. Recent years have also seen considerable increase in irrigation through underground pipes in some sodicity-affected areas like north-western India. This means that alternative technologies amenable to amendment mixing in the irrigation waters need to be developed for the sustained use of sodic waters in irrigation (ICAR-CSSRI 2017). In addition to these constraints, steadily declining availability and quality are perhaps the most formidable roadblocks to the use of mined gypsum as an ameliorant. For example, of the total 'remaining gypsum resources' in India only about 1% are placed in surgical plaster and soil reclamation grades (IBM 2015). As the competition for gypsum use intensifies, infrastructure and industrial sectors may likely grab a considerable portion of even agricultural-grade gypsum further reducing its availability on the market. In so far as Indian scenario is concerned, laboratory estimations have revealed poor quality of currently available gypsum in terms of very low Ca content ($\approx$40%) than its prescribed concentration $\geq$ 70% (ICAR 2018). Evidently, interest has increased manifold in harnessing the alternative amendments for sodic soil reclamation.

Depending on factors like soil texture and crops to be grown, reduced amounts of gypsum may be as effective as its full dose (100% GR). Gypsum at 50% GR was as effective as 100% GR in increasing the rice yield in a fine-textured saline-sodic (non-gypsiferous) soil. Gypsum applied at 50% GR also gave significantly better yields than an equivalent sulphur dose, attributed to the slow-reacting nature of sulphur (Hussain et al. 1988). Ahmad et al. (2016) evaluated the effects of gypsum at four rates (no gypsum, GR25%, GR50% and GR75%) in variably textured saline-sodic soils [EC_e ~8 $dS\,m^{-1}$, SAR ~44 $(mmol\,L^{-1})^{1/2}$ and ESP ~41%]. When leached with low-carbonate water [EC 0·39 $dS\,m^{-1}$, SAR 0·56 $(mmol\,L^{-1})^{1/2}$ and RSC 0·15 $mmol_c\,L^{-1}$], marked improvements in hydraulic conductivity and decreases in EC_e and SAR were seen with GR25%, GR50% and GR75% in loamy sand, sandy loam and clayey loam soils, respectively. Singh et al. (2009b) found that integration of salt-tolerant varieties of rice (CSR 13) and wheat (KRL 19) could further reduce the GR to 25% in the sodic soils of Indo-Gangetic Plains. The grain yields obtained in 25% and 50% GR treatments did not differ significantly. Salt-tolerant varieties receiving 25% GR not only outperformed their locally popular counterparts but could also help in saving ~43% of the total expenditure on gypsum (50% GR) application with salt-sensitive traditional varieties.

20.2.1.2 Synthetic Gypsum

Synthetic gypsum is a collective term to describe the industrial by-products having potential use as soil ameliorants and conditioners. Such synthetic products include flue gas desulphurization gypsum (FGDG), phosphogypsum (PG), titanogypsum (TG), fluorogypsum (FG) and citrogypsum (CG) which are by-products of coal-fired power plants, phosphoric acid, titanium dioxide, hydrofluoric acid and citric acid manufacturing, respectively (http://www.fgdproducts.org/). Of these, FGDG and PG have been studied by many authors for their ameliorative effects in sodic soils. A long-term study revealed that FGDG treatment led to marked reductions in soil pH, ESP and EC in the top 0–20 cm soil with their values decreasing by ~92%, 58% and 95%, respectively, compared to the initial values after 4 years of application. FGDG-treated soils also showed higher concentrations of $Ca^{2+}$and SO_4^{2-} and low concentrations of HCO_3^- and CO_3^{2-} ions. Sunflower and corn yields gradually increased over time, registering an increase of over 90% than yields in non-reclaimed soils. Again, heavy metal (Cd, As, Pb, Hg and Cr) concentrations in treated soils and crops were not detected, demonstrating the benign nature of FGDG (Zhao et al. 2018). Similarly, FGDG incorporation decreased the pH, ESP, clay dispersion and soluble Na^+ while increased soluble $Mg^{2+}$and K^+ levels in a calcareous sodic soil, leading to higher germination rate and corn production than control (Chun et al. 2001). In addition to a potential reclaimant for sodium-affected soils, FGDG can also be used as a source of Ca and S and as an acid soil ameliorant (DeSutter and Cihacek 2009). Commercial use of FGDG as a sodic soil ameliorant is likely to increase in the future. In the United States, for example, most of the FGDG was initially used in the wallboard industry. Of late, however, it is increasingly being used as an agricultural amendment (Chen and Dick 2011). Nonetheless, increasing uses warrant precautions in FGDG application to avoid the potential negative impacts on soil health and agricultural production. This consideration stems from the fact that FGDG contains appreciable amounts of heavy metals that may inadvertently be added to the soil. Although soil pH, EC and ESP decreased, As and Hg concentrations in ameliorated soils were found to be positively correlated with FGDG added, implying that environmental risks associated with applying FGDG need to be cautiously assessed (Chen et al. 2015).

Phosphoric acid (a source of water-soluble P) and its by-product phosphogypsum (PG) have also been found effective in reducing the sodicity stress. A calcareous saline-sodic soil was reclaimed by adding phosphoric acid into moderately saline leaching water in a lysimeter experiment. Interestingly, phosphoric acid was more effective than chemical equivalent PG in decreasing soil ESP and in improving hydraulic conductivity. Soil ESP in different leaching treatments was 10 (water only), 5.5 (phosphoric acid) and 5.9–8.2 (PG). Despite promising results and nearly one-third cost than PG, authors expressed the need for more studies to establish phosphoric acid as an acceptable ameliorant under field conditions (Gharaibeh et al. 2010). A sandy clay loam saline-sodic soil (pH_s 8.6, EC_e 21 dS m^{-1}, SAR 183.7 and GR 5.6 me 100 g^{-1}) leached with synthetic water (EC 2 dS m^{-1}, SAR 12, RSC 3 me L^{-1}) displayed better improvements when pretreated with PG (at 50 and 100% GR) than with FYM (at 25 and 50 Mg ha^{-1}). It was concluded that Mg-rich saline waters (Mg:Ca ratio 4:6) can be used for reclaiming saline-sodic soils provided an appropriate amendment capable of releasing soluble Ca is used (Ghafoor et al. 1992). Incorporation of PG ameliorated an oilfield brine-contaminated field as evidenced by reduced EC, SAR and ESP levels in 0–15 cm depth. Furthermore, PG application did not increase the levels of trace elements in barley plants. Excessive amounts of B and Cd in barley tissues were presumably due to brine spill (Liang et al. 1995). Applications of dry granular PAM (20 kg ha^{-1}) along with PG or PG alone were effective in maintaining final IR > 12 mm h^{-1} and low run-off in smectitic clay soils having varying levels of ESP (2–20) and exposed to simulated distilled water rainstorms. Contrarily, soils without PAM or PG displayed decrease in final IR from 14 to 2 mm h^{-1} and increase in run-off and erosion when ESP increased to 20 (Tang et al. 2006). In addition to ameliorative effects, PG can also be a major source of S and Ca for crops, can overcome subsoil acidity and Al toxicity and may improve soil aggregation. However, in contrast to the mined gypsum, PG contains impurities that might accumulate in the soil and groundwater (Alcordo and Rechcigl 1992). A calcareous sodic soil (pH 9.2, SAR 13.7, ESP 35, $CaCO_3$ 9.5%) medium in metallic cations (Fe, Mn, Zn and Cu) reclaimed by one time application of pressmud (0, 5, 10 and 15 t ha^{-1}) or spent wash (0.25, 0.5 and 0.75 million L ha^{-1}) in combination with PG (0, 25% and 50% GR) showed increased levels of metallic cations (Fe, Mn, Zn, Cu, Ni, Cd and Pb). Although highest values of metallic cations were detected when either pressmud or spent wash were used conjunctively with PG, their concentrations were still below the permissible limits indicating that one time conjunctive use may not harm the soils and crops (Pagaria and Totawat 2007). Although a few reports indicate the potential of titanogypsum (Meriño-Gergichevich et al. 2010) and citrogypsum (Kost et al. 2007) as probable amendments for acidic soils, their effects on alleviating sodicity stress remain unknown.

20.2.1.3 Marine Gypsum

Shrinking availability of mineral gypsum and potential limitations in the use of by-product gypsum has prompted the interest in using marine gypsum (MG) for reclaiming the sodic soils. A by-product of common salt manufacturing by solar evaporation in the coastal regions, MG contains about 90.0% $CaSO_4.2H_2O$, up to 2.0% NaCl, 0.57% $MgCl_2$, 3.4% $MgSO_4$ and up to 8.0% insoluble materials (IBM 2015). Presence of NaCl, $MgCl_2$ and $MgSO_4$ salts in appreciable amounts may increase the ionic strength of aqueous solution by decreasing its activity coefficient resulting in increased solubility of gypsum and higher reclamation efficiency than mined gypsum (ICAR-CSSRI 2017). A field experiment revealed that mixing of marine gypsum (50% GR) into sodic soils followed by the leaching with water (pH 7.7, EC 0.87 dS m^{-1}, RSC1.0 mmol L^{-1} and SAR 1.16) resulted in the greatest increase in the rice yield compared to mineral gypsum and control treatments. The maximum reduction in soil pH (0.99 units) was also observed in 50% GR MG treatment. However, soil EC slightly increased probably due to increased ionic activity of the solution maintaining adequate electrolyte concentration in the soil solution (ICAR-CSSRI 2018). It is observed that by-product gypsum and marine gypsum availability in India is comparable to the total mineral gypsum currently available (IBM 2015), indicating the need for convincing evidence that can pave the way for their commercial use in sodic soil reclamation.

20.2.1.4 Other Industrial By-products

Some other major industrial by-products that have been in use for reclaiming the sodic soils include pyrite, elemental sulphur, fly ash, pressmud and distillery spent wash. Pyrite (both FeS_2) occurs in many sedimentary and hard coal deposits. Upon purification, hard coals yield pyrite as a by-product. Pyrite has long been used as a source of sulphur (S) and iron (Fe) to crop plants and also as an amendment for sodic soils (van Straaten 2002; Wallace and Wallace 1992). Several studies have indicated the positive influence of pyrite, especially when supplemented with an organic source, in reducing sodicity hazard. According to Tiwari et al. (1982) pyrite application at 40% and 80% GR increased the rice grain yield by over twofold. Grain yields of the succeeding wheat and rice crops also increased significantly owing to residual effects of pyrite application. Increased crop yields were attributed to appreciable reductions in soil pH, EC, ESP and soluble sodium content resulting in enhanced uptake of Zn and Ca by the crops. Dubey and Mondal (1993) found that a saline water (EC_{IW} 4 dS m^{-1})-irrigated sodic soil (pH 10.6, ESP 95%) displayed appreciable reductions in pH and ESP and higher rice and wheat yields when ameliorated with pyrite (50% GR) and FYM (1%). Ram and Pal (1994) observed that pyrite application (3.94 t ha^{-1}) mitigated the adverse effects of high RSC water (20.0 meq L^{-1}) on soil properties and wheat yield. While soil pH and ESP decreased, hydraulic conductivity increased markedly over the years leading to significant improvements in wheat grain and straw yields. Singh et al. (2009a) reported marked reduction in salt stress coupled with increase in infiltration rate and nutrient availability in sodic (RSC 10–20 me L^{-1}) water-irrigated pearl millet-wheat rotation. Sharma and Swarup (1997) evaluated the effects of pyrites (total S 22%; water-soluble S 1–8%) and gypsum on the soil properties and yields of rice and wheat in alkali soils. The efficiency of pyrites in decreasing soil pH and ESP and in increasing crop yields was dependent on their water-soluble S content with pyrites containing 5.5% and 8% soluble S being as effective as gypsum. In contrast, freshly mined pyrite with 1% water-soluble S was found to be inefficient in reclaiming the alkali soils. When stored under moist conditions by sprinkling water, Fe- and S-oxidizing bacteria increased leading to rise in water-soluble S from 1% to 5% within a period of 6 months. Despite these beneficial effects, widespread commercial use of pyrite has been hampered by its slow oxidation and the presence of heavy metals. After application, pyrite may take years for complete oxidation with factors like particle size, method of application and the degree of impurity playing a critical role in oxidation. In general, finer surface applied pyrite tends to oxidize rapidly especially when some kind of oxidation has occurred prior to application. Better results obtained with impure pyrite can be ascribed to the presence of microbes and iron, oxidation products that catalyse further oxidation and lower the pH than pure forms (Wallace and Wallace 1992). Certain sulphide- and iron-oxidizing bacteria increase the rate of oxidation significantly at optimum pH (3–5), moisture and aeration. Oxidation rate reduces with increase in soil pH and virtually ceases at pH level ≥ 9. Inoculation of pyrite with *Thiobacillus ferrooxidans* can hasten the rate of oxidation resulting in improved pyrite efficiency (Sharma and Swarup 1997). Presence of metal impurities through conducive to oxidation is also a major barrier to the sustainable agricultural uses of pyrite.

Some researchers have also reported efficacy of elemental sulphur in improving the quality of sodic soils. While gypsum or elemental sulphur alone did not give satisfactory results, elemental sulphur inoculated with *Acidithiobacillus* markedly decreased soil pH in the leaching solution, especially when applied in higher amounts in a Brazilian solodic soil. The highest reductions in soil EC and exchangeable Na^+, Ca^{2+} and Mg^{2+} were noted when inoculated sulphur and gypsum were used in equal ratios (Stamford et al. 2007). Although both sulphur and gypsum in general improved soil properties and rice-wheat yields in a saline-sodic soil [EC_e 6.1 dS m^{-1}, pH_s 9.2 and SAR 41.7 (mmol $L^{-1})^{1/2}$], best results were obtained when they were applied at 100% GR (Ahmed et al. 2016). Similar to pyrite, slow oxidation is a prominent limitation to sulphur use in sodic soils. High root zone pH reduces oxidation, lowering the reclamation efficiency. In order to be as effective as soluble calcium salts, soil-applied sulphur must undergo oxidation to generate sufficient sulphuric acid for replacing the exchangeable Na^+. Due to impeded oxidation, sulphur fails to match the effects of gypsum or sulphuric acid even when used in chemically equivalent amounts (Abrol et al. 1988). A recent study showed that different combinations of reliance elemental sulphur (RES) and gypsum were comparable to 50% GR in reducing the pH of variably textured sodic soils with RES applied 21 days before rice transplanting resulting in greater reduction than other days of application. However, application method, water management and particle size did not differ significantly with regard to lowering the soil pH (ICAR-CSSRI 2018).

Fly ash (FA), a by-product of coal-powered power plants, poses constraints in safe disposal. Accordingly, efforts have been made to utilize it in soil reclamation programmes. Application of FA, either alone (Tiwari and Kumar 1985) or in combination of other amendments like gypsum (Kumar and Singh 2003), lowers soil pH, ESP and associated problems in sodic soils with concurrent improvements in nutrient availability and crop yields. Conjunctive use of FA with gypsum may result in reduced use of the latter (Kumar and Singh 2003). Notwithstanding the positive effects of FA in sodic soils, it may sometimes raise the soil pH, salinity and heavy metal concentrations in the ameliorated lands (Carlson and Adriano 1993).

Pressmud (PM), a by-product of sugar industry, is considered a rich source of plant nutrients. Sugar manufactured through sulphitation and carbonation processes results in the production of acidic sulphitation pressmud (SPM) and lime-rich carbonation pressmud (CPM), respectively, which can be used for the reclamation of alkali and acidic soils (Solaimalai et al. 2001). Effects of wheat residue management, *Sesbania* green manure (SGM) and SPM with or without chemical fertilizers were studied on sodic water [RSC 8.5 me L^{-1} and SAR 8.8 $(mmolL^{-1})^{1/2}$] on irrigated rice and wheat crops. Increases in grain yields under different management practices, viz. NP fertilizers (120 and 26 kg ha^{-1}) with wheat residue burning or wheat residue ploughing (WRP) or WRP plus SGM or WRP plus SPM, were ~6%, 25%, 26% and 27% for rice and ~1%, 10%, 17% and 16% for wheat, respectively, over recommended dose of fertilizers (NP fertilizers 120 and 26 kg ha^{-1}) alone. Results indicated that incorporation of wheat residue 50 days before rice transplanting and SGM or SPM application along with the recommended fertilizer dose was the best practice for sustaining the productivity of rice-wheat system in sodic groundwater areas of Indo-Gangetic Plains (Yaduvanshi and Sharma 2007). Incorporation of phosphogypsum (25% GR) along with pressmud or spent wash decreased the soil pH, EC and ESP of a saline-sodic soil. The highest wheat grain yield was recorded when phosphogypsum was applied alone or in combination with pressmud (15 Mg ha^{-1}) or spent wash (750 thousand L ha^{-1}). Phosphogypsum above 25% GR had no significant effect on wheat grain and straw yields (Pagaria and Totawat 2007). Pressmud addition (20 Mg ha^{-1}) improved soil quality and maize biomass in a saline-sodic soil. However, the beneficial effects of pressmud were more pronounced in less saline [EC 5.4 dS m^{-1}, SAR 18.7 $(m\ mol\ L^{-1})^{1/2}$] than in relatively more saline-sodic [EC 6.2 dS m^{-1}, SAR 20.7 $(m\ mol\ L^{-1})^{1/2}$] soils (Muhammad and Khattak 2009). Pressmud alone did not increase crop yields significantly in a non-gypsiferous heavy saline-sodic soil. In contrast, FYM application resulted in significantly higher rice yields than control (Hussain et al. 1988). Application of organic amendments (FYM and *Sesbania* green manure) led to the highest increase in wheat yield in a salt-affected soil which was at par with pressmud (Khan and Khan 2010). These observations indicate that supplementing organic amendments with pressmud can give better results, especially when salt stress is high.

Distillery spent wash (DSW), a waste product of alcohol industry, may cause environmental problems when disposed unsafely warranting the development of safe practices for its management. Distillery wastewater has enormous potential for the production of biogas and the production of nutrient-rich post-methanation effluent (PME). According to estimates, PME can constitute a significant source of plant nutrients (NPK) reducing the dependence on chemical fertilizers (Kamble et al. 2017). There is evidence that PME could also be an efficient potential organic ameliorant for sodic soils (Kaushik et al. 2005; Pathak et al. 1999). Some of the major effects of PME application include increased activity of soil enzymes, increase in soil organic carbon and nutrient availability and reduction in soil pH. Nonetheless, increase in the salinity of PME-treated soils may sometimes be a major limitation to its commercial applications.

20.2.1.5 Crop Residues, Manures and Composts

Crop residues, otherwise treated as a problematic waste, hold considerable potential for improving soil productivity when used properly. Application of crop wastes and residues improves soil aggregation, organic carbon and water retention. A thin layer of mulch insulates the soil from the erosive impact of rain drops, arresting run-off-induced soil loss. It also protects the soil from scorching heat, reducing the evaporative loss of water (Mulumba and Lal 2008). These effects, besides leading to general improvements in soil quality, can contribute considerably to improving water availability and lessening the salt accumulation in saline and sodic soils (Pang et al. 2010; Tejedor et al. 2003).

Application of organic manures and composts also improves the productivity of salt-affected soils by improving soil cation exchange capacity and water and nutrient availability to plants (Hanay et al. 2004), albeit at significantly lower costs than chemical amendments. FYM application considerably reduced the adverse impacts of sodic water irrigation (RSC 10–12.5 m mol L^{-1}) on calcareous soils resulting in 38% and 26% higher rice and wheat yields over control. Interestingly, gypsum application (50% GR) led to only about 18% yield increase in both the crops. However, combined application of FYM and gypsum was not effective in further increasing the yield, indicating that FYM alone could efficiently hasten $CaCO_3$ dissolution under such conditions (Choudhary et al. 2011). Another study suggested that although FYM application alone decreased the soluble salts and exchangeable Na^+ leading to higher water infiltration rate in a sodic soil (pH 9.3), addition of gypsum further enhanced these ameliorative effects of FYM (Makoi and Ndakidemi 2007). In spite of being a cost-effective alternative to chemical amendments, organic manures are required in greater amounts, posing difficulties in collection and application. Again, regular applications of some of the organic manures can also hasten salt accumulation, necessitating ample precautions in their use.

Municipal solid waste compost (MSWC) is also increasingly being tapped as potential resource for augmenting crop productivity while doing away the risks in the disposal of urban wastes. MSWC application can accelerate the dissolution of precipitated $CaCO_3$, increasing the soluble Ca^{2+} availability for replacing Na^+ ions from the exchange complex (Avnimelech et al. 1992). MSWC, either alone or in combination with 50% of the recommended dose of fertilizers, improved the activity of many soil enzymes (dehydrogenase, alkaline phosphatise and urease), microbial biomass carbon and nutrient availability in a saline-sodic soil (EC_e 7.2 dS m^{-1}, pH 8.4) leading to significant increases in the grain and straw yields of mustard and pearl millet crops (Meena et al. 2016). Gypsum-treated saline-sodic soils (pH 9.7, EC 12.6 dS m^{-1}, ESP 44.2) displayed appreciable reductions in salinity and sodicity, but physical properties did not improve. In contrast, addition of MSWC besides reducing the salt content also markedly improved soil hydraulic conductivity, organic matter and the formation of water-stable aggregates, reflecting synergistic effects of MSWC incorporation (Hanay et al. 2004). However, MSWC application may sometimes inadvertently increase heavy metal concentrations, suggesting the need for laboratory analysis to ensure the safe field application.

20.2.1.6 Bio-augmented Materials

The problems encountered in the use of conventional inorganic amendments like gypsum have prompted the evaluation of specially formulated bio-augmented amendments for reducing the sodicity stress in an environment-friendly manner. Increasing emphasis on bio-augmented materials stems from the fact that combined use of two or more organic sources may give far better results than the application of a single amendment and may also reduce the dependence on relatively costly amendments like gypsum. One such bio-augmented formulation (SF_{OA}) consisting of vermicompost (inoculated with plant growth-promoting fungi), pressmud and neem (*Azadirachta indica*) seed cake, when applied along with the recommended dose of fertilizers, significantly increased wheat grain yield and quality than control by improving total organic C and soil enzyme activities in a silty loam sodic soil (pH 9.2, ESP 60) (Srivastava et al. 2016). When applied after gypsum (25.0 Mg ha^{-1}), this formulation (SF_{OA} at 10 Mg ha^{-1}) also significantly improved biomass and withanolide production in *Withania somnifera* under similar conditions. Favourable effects of combined SF_{OA} and gypsum use were ascribed to decreased soil bulk density and pH coupled with increased water-holding capacity, total organic C and soil enzyme activities (alkaline phosphatase, β-glucosidase, dehydrogenase and cellulose) (Gupta et al. 2016).

20.2.1.7 Biochar

Biochar (biomass-derived black carbon), refers to the black carbon formed by the incomplete combustion of biomass in an oxygen-free environment. In addition to major use as a potential long-term sink for sequestering the atmospheric CO_2, biochar is increasingly being used for improving the soil properties and crop yields (Jha et al. 2010). Of late, several studies have shown the utility of biochar in reclaiming salt-affected soils. Biochar derived from *Acacia pycnantha* biomass improved plant growth of *Eucalyptus viminalis* in a highly saline-sodic soil (EC_e 49.4 dS m^{-1}, ESP 45.1), suggesting that it could be a viable intervention for establishing tree plantations under such conditions (Drake et al. 2016). Effects of flue gas desulphurization gypsum (FGDG at 33.6 Mg ha^{-1} and 66.2 Mg ha^{-1}) and sugar beet (*Beta vulgaris*) biochar (16.8 Mg ha^{-1}), either alone or in combination, were studied in a saline-sodic soil. Addition of FGDG increased soil EC_e from 3.5 to 8.4 dS m^{-1} but decreased SAR_e from 16 to 9. Contrarily, biochar application increased total organic carbon (TOC) and soil respiration rate. When used conjunctively, however, TOC did not significantly improve, EC_e increased from 3.5 to 7.7 dS m^{-1}, SAR_e decreased from 16 to 9, and soil respiration rate increased for all measurements (Schultz et al. 2017). Individual and synergic effects of biochar (B), humic substances (HS) and gypsum (G) were studied on soil properties and quinoa plant growth in a saline-sodic soil. Soil EC_e, SAR and ESP decreased significantly in all the treatments. In comparison to control, ESP decreased by 11-fold with gypsum and by 9–13-fold in rest of the treatments. Similarly, soil microbial biomass increased by 112% and 322% in the B + HS + G treatment in quinoa genotypes AZ-51 and AZ-103, respectively, implying that combined application of biochar, humic substances and gypsum was an effective means for reclaiming the degraded saline-sodic soils (Alcívar et al. 2018).

20.2.1.8 Super-absorbent Polymers

Superabsorbent polymers (SAPs), popularly referred to as hydrogel, are natural or synthetic, cross-linked water-absorbing polymers. Many studies have shown that incorporation of SAPs into soil or irrigation water can overcome salt stress either directly (i.e. soil amelioration) or indirectly (i.e. modulation of plant metabolism). Again, in some cases, both direct and indirect effects may partly contribute in improving plant performance under saline conditions. Conjunctive use of vinyl alcohol acrylic acid and compost improved soil structural stability and plant available water in a saline-sodic soil (Emami and Astaraei 2012). Substantial improvements in soil porosity and plant-available water together contributed in reducing the effects of saline irrigation in a SAP-treated sandy loam soil (Shokuohifar et al. 2016). Polyacrylamide (PAM; 10 and 20 ppm) mixed into saline irrigation water (EC_{iw} 6.2 dS m^{-1}) increased the soil water sorptivity in pomegranate orchards (Tadayonnejad et al. 2017). PAM (10 ppm) application accelerated root zone water flux in a saline-irrigated shrink-swell orchard soil. This in turn hastened Na^+ leaching and $CaCO_3$ dissolution, resulting in reduced EC_e and SAR at different soil depths (Ganjegunte et al. 2011). Addition of a hydrogel polymer into the growing medium improved salt tolerance of tomato (*Lycopersicon esculentum*), lettuce (*Lactuca sativa*) and cucumber (*Cucumis sativus*) by increasing the leaf succulence, protecting the leaf pigments, increasing the carbon assimilation and upregulating proline accumulation (El-Sayed et al. 1991). Hydrogel application increased the yield of salt-stressed cabbage (*Brassica oleracea*) plants but at the cost of increased Na^+ concentration in soil solution, suggesting the need to develop compounds that would not release salt ions into soil solution (Silberbush et al. 1993). Beneficial effects of hydrogel in improving the plant biomass of salt-stressed *Populus euphratica* were ascribed to salt exclusion and higher absorption of Ca^{2+} (Chen et al. 2004).

20.2.1.9 Nanomaterials

Recently, the interest in nano-enhanced materials as novel ameliorants for degraded lands has considerably increased. Also referred to as engineered nanoparticles (ENPs), such compounds can be categorized into metal ENPs (e.g. elemental Ag and Fe), fullerenes (Buckminster fullerenes and nanocones), metal oxides (TiO_2, CuO and FeO_2), complex compounds (Co-Zn-Fe oxide) and polymer-coated quantum dots (cadmium-selenide and polystyrene) (Dinesh et al. 2012). ENPs, by improving the infiltration rate and soil aggregate stability, decrease the surface run-off and structural instability in sodic soils. Application of urban solid waste compost-coated sulphur (15 t ha^{-1}) and nano iron oxide powder (20 mg kg^{-1}) decreased the pH and SAR of a saline-sodic soil resulting in increased availability of nutrients to sunflower plants. By comparison, their solitary applications marginally raised the soil EC_e (Ghodsi et al. 2015). Polymeric aluminium ferric sulphate (PAFS) application decreased the soil pH, EC, bulk density and $CaCO_3$ while increasing the saturated hydraulic conductivity from 0.05 mm d^{-1} to 40.01 mm d^{-1} in a highly dispersed saline-sodic soil. Rice yield in PAFS-treated plots was 4.66 Mg ha^{-1} compared to only 0.83 Mg ha^{-1} in control (Luo et al. 2015). Nano-gypsum (100% GR) was found very promising in reducing the soil pH and ESP compared to mined gypsum applied at GR 25, 50, 75 and 100% GR (Kumar and Thiyageshwari 2018). Among 17 different amendments, hydrolysed polymaleic anhydride (HPMA) was found the most effective in promoting the plant growth by decreasing the pH, EC and bulk density and increasing clay flocculation and water infiltration rate in a saline-sodic soil (Wang et al. 2011)

20.3 Engineering Interventions

20.3.1 Improving the Land Drainage

Deep-rooted flaws in the irrigation schemes often result in the excess use of irrigation water, while the drainage component is virtually completely ignored. Over the years, indiscriminate irrigation and neglect of drainage eventually lead to the water accumulation in the root zone or even on soil surface rendering the affected lands uncultivable. In addition, seepage from uplands and unlined canals, congestion of natural drains, heavy downpour and flash floods may also contribute to surface waterlogging and the attendant rise in salinity. The fact that waterlogging also causes salinity build-up in croplands can be explained by the gradual rise of dissolved salts from the lower to upper soil layers. Continuous upward flow of saline water from the water table to surface results in the salt accumulation in soil profile. Presently, this situation can be seen in many parts of the Mediterranean Basin, Indo-Gangetic Plains and the Murray-Darling Basin. While the judicious use of irrigation water, adoption of improved irrigation practices and adequate drainage remain the keys to maintaining the regional water and salt balances, specific drainage interventions become absolutely essential for rehabilitating the waterlogged salty lands.

20.3.1.1 Surface Drainage

Surface drainage, also called the open drainage, refers to the removal of excess rain, flood or irrigation water accumulating over the land surface by making the open ditches, field drains and similar structures. The land should be gently sloped to permit the easy flow of excess water toward such structures. Although surface drainage is considered necessary mainly in humid climate, the problem of surface water stagnation may also be frequently seen in irrigated arid and semiarid regions, especially when the annual rainfall exceeds 500 mm. Adverse edaphic conditions including flat topography, shallow water tables and presence of a hard subsurface layer impenetrable to water may further exacerbate the problem. For example, water stagnation on the surface for extended periods of time has been reported from the irrigated semiarid parts of Haryana state of India. Contrary to the popular perception that surface drainage is an efficient practice for overcoming waterlogging in irrigated commands, it is worth mentioning that adequate surface drainage cannot completely arrest the rise in water table, suggesting the need for subsurface interventions (Gupta 2000).

20.3.1.2 Subsurface Drainage

Subsurface drainage (SSD) of waterlogged saline lands can be achieved through ‘vertical’ and ‘horizontal’ methods. In the vertical SSD, groundwater is pumped out using tube wells or dug wells. In areas where canal networks do not exist, vertical drainage is merely a means of irrigation. In canal-irrigated areas, however, it can be one of the interventions for keeping the water tables in check by promoting the conjunctive use of canal and groundwater. In certain situations, large-scale installation of tube wells may in fact become necessary for lowering the water table to prevent salt accumulation in the root zone. Besides direct use in irrigation, the pumped groundwater can also be discharged into canals for improving the water supplies to the farms at tail end. A large-scale public tubewell program, implemented in the Indus Basin of Pakistan to control waterlogging and salinity problems, witnessed the installation of ~14,000 tube wells covering ~2.6 M ha of freshwater-irrigated lands (Qureshi et al. 2008). However, vertical drainage sometimes instead of checking the problem may actually exacerbate salinity and water stresses as evidenced by massive secondary salinization and groundwater depletion in canal and tube well-irrigated areas of north-western India. It often happens that farmers’ grappling with reduced or erratic canal water supplies become overly dependent on groundwater, a practice which over time alters the water and salt balances in ways detrimental to sustainable land use (Gupta and Abrol 2000). Again, operation and maintenance of a large number of tube wells, especially in areas with cheap and subsidized electricity, may also become a burden for the government. Excessive lowering of groundwater level can also accelerate the mixing of saline groundwater into freshwater aquifers, deteriorating the water quality and increasing the pumping cost (Qureshi et al. 2008). It is due to these reasons that the progress of vertical drainage has been abysmally slow, increasing the emphasis on horizontal SSD.

The horizontal SSD system consists of a network of concrete or polyvinyl chloride (PVC) pipes along with filters installed manually or mechanically at a specified depth and spacing below the soil surface. Both depth and spacing are the critical factors governing the rate of salt removal. Results of a long-term (8 year) investigation in a semiarid area (Haryana, India) revealed that SSD system installed at a 1.75 m depth with three drain spacings (25, 50 and 75 m) facilitated the speedy reclamation of a severely waterlogged barren saline land. Salt leaching from the root zone increased the soil porosity, infiltration rate, organic carbon, available NPK and available water and decreased the bulk density, albeit differently in three drain spacings. The rate of salt removal varied initially with drain spacing, but variations were reduced within a few years making the land suitable for most of the crops. Plots with a drain spacing of 75 m required more time for complete reclamation compared to those with 25 m or 50 m spacing. Nonetheless, gradual reductions in soil salinity levelled the yields in different drain spacings by the fourth year. Based on installation cost and other factors, drain spacing of 75 m was adjudged to be the best option in areas having monsoon climate where rainfall can also contribute to the natural leaching of salts (Sharma et al. 2000). Another study conducted in the vertisol soil region of Tungabhadra Irrigation Project of Karnataka, India, showed that SSD installation lowered the water table and soil salinity with increase in crop yields and cropping intensity in the drained area even at unusually wide (150 m) drain spacing. Cultivation of submerged lowland rice further aided in salt leaching within 1 year. Although originally thought to function as interceptor drains for preventing the seepage water from the canals, comparable values of EC of drainage effluent in all the three drains led to the conclusion that the system was in fact working as a normal SSD rather than as an interceptor system (Manjunatha et al. 2004). A study from the Harran plain area of Turkey revealed that SSD installation decreased the salinity by ~80% in the top 20 cm soil after 3 years. However, winter rainfall had no significant effect on salt leaching (Bahceci and Nacar 2009).

Notwithstanding these benefits, SSD implementation often confronts a suit of socio-economic constraints rendering it in somewhat less appealing proposition to reclaim the salty lands. In contrast to other salinity mitigation practices suited to 'individual' farmer needs, SSD is essentially a community-based action. Besides prohibitive initial costs restricting the technology spread, poor community response may make continued operation difficult in many areas underscoring the need for public-private partnerships to lower the establishment costs and campaigns to sensitize the community of long-term benefits (Ritzema et al. 2008). Some authors advocate that a co-operative institutional setup, by removing the disparities in benefit sharing, might overcome the problems arising due to weak community involvement (Datta and Joshi 1993). Safe disposal of saline drainage waters can also impose formidable limitations in the landlocked SSD areas away from the seas. This problem can partly be overcome by constructing the evaporation ponds, conjunctive use of saline and fresh waters, cultivation of salt-tolerant crops and saline aquaculture. Among these options, the last three have gained currency in the last few years.

20.3.1.3 Reuse of Saline Drainage Effluent

Saline drainage water, otherwise considered to be an environmental hazard, can be recycled to produce crops, aquatic resources and in soil reclamation as well, obviously with aid of improved technologies. Considering the fact that disposal of saline effluent in far flung areas may be cost prohibitive and tedious, efforts have been made to utilize it as a source of irrigation for reducing the drainable volumes and producing the additional crop yields. Reuse in irrigation is particularly an attractive option in regions having freshwater supplies so that at least pre-sowing irrigation can be done using the good-quality water. Saline drainage water, reused in cyclic or blending mode, can also partly contribute to the lowering of shallow water tables. Long-term experiments have shown that saline drainage waters can profitably be used for producing wheat, pearl millet, sorghum and sunflower crops with only slight to moderate reductions in grain yields (Sharma and Rao 1998; Sharma et al. 2005), especially if canal water is available for blending and for providing a few irrigations at critical stages. The prospects of using saline effluents in irrigation become more appealing in areas with relatively higher rainfall so that a considerable portion of salts accumulated during the irrigation season are washed away below the root zone. Cultivation of crops capable of enduring excess salts may further increase the acceptability of this practice. Observations from the Indus Valley of Pakistan, where ~80% of the groundwater is too salty, suggest that integrated use of salt-tolerant cultivars, amendments and conjunctive irrigations with fresh and saline water can substantially improve the quality of saline-sodic soils to the extent that salt-tolerant cultivars of rice (e.g. SSRI-8) and wheat (e.g. SIS-32) can produce acceptable yields (Ghafoor et al. 2012; Murtaza et al. 2009).

Saline effluents, with or without amendments, can also be harnessed for reducing the soluble salt and exchangeable Na^+ contents by leaching. Application of dilute (60 meq L^{-1}) or concentrated (120 meq L^{-1}) saline waters decreased pH and EC in saline-sodic inceptisols (Basak et al. 2015). Ponding of sugar mill wastewater decreased the EC and ESP of a saline-sodic soil by 90% and 30%, respectively (Kameli et al. 2017). Leaching with dilute saline water (DSW, EC_{iw} 5 dS m^{-1}) or concentrated saline water (CSW, 10 dS m^{-1}) decreased pH of normal, saline (pH_2 7.7 and EC_e 10.6 dS m^{-1}) and alkali (pH_2 9.15 and EC_e 2.9 dS m^{-1}) soils and ESP of the alkali soil (Arora et al. 2012). Use of low-quality water in soil reclamation can spare large amounts of fresh water for irrigating the high-value crops. However, precaution is particularly essential in areas where natural and/or constructed drainage systems do not exist. In lands lacking drainage, salts leached to the lower levels will still remain in the system, though at lower depths, and can move upward to cause secondary salinity.

In the last few decades, interest in saline aquaculture has also grown considerably. In certain parts of north-western India, where salt-induced land degradation has attained alarming proportions, fish and shrimp production can be the only viable land use option. Commercial fish culture was successfully done in extremely saline pond water (≈25 dS m^{-1}) in an inland salinity-affected land of north-western India. Despite high salinity of pond water, low water availability and high evaporative losses, fish growth was about 400–600 g in 6 months and 600–800 g in 1-year period (CSSRI 2013). Widespread deficiencies of K^+ in inland saline waters (10 g L^{-1} salinity) imposing limitations to shrimp (e.g. tiger shrimp *Penaeus monodon*) cultivation can be overcome by supplemental use of muriate of potash (KCl) (Purushothaman et al. 2014). Commercial cultivation of high-value seaweeds can be a profitable venture in poorly drained coastal saline lands (Subba Rao and Mantri 2006). Land shaping models have paved the way for commercial fish culture in waterlogged salt-affected lands of central Indo-Gangetic Plains and some saline coastal areas of India.

20.3.1.4 Dry Drainage

The preceding account makes it evident that though effective surface and subsurface drainage techniques may not always be compatible with the socio-economic milieu and the environment. Owing to such limitations, some experts propose dry drainage as an alternative solution. In this method of drainage, a certain part of the cultivated land is kept fallow such that it can act as an evaporative sink drawing a portion of water and salt from the irrigated areas (Konukcu et al. 2006). Drainage by evaporation from fallow areas literally implies imposing ‘retirement on a part of irrigated land’ while the rest of the area continues to be cropped with normal irrigation. In order to be effective, shallow water table and high evaporation rates characteristic of arid and semiarid regions must prevail. Depending on factors like soil properties, crops grown and climatic conditions, appropriately designed dry drainage schemes may permit optimum land use (Khouri 1998). A study conducted in the Hetao Irrigation District of China assessed the effectiveness of dry drainage by using remote sensing, a conceptual model and a field experiment. Results indicated that it could be an efficient alternative means of controlling soil salinity in arid and semiarid areas where artificial drainage interventions are not applicable (Wu et al. 2009).

20.3.2 Land Shaping Models

Vast areas of irrigated croplands remain seasonally or permanently waterlogged in many irrigated commands of the world. In comparison to permanent waterlogging, subsurface waterlogging and associated problems remain undetected for years and may eventually lead to land abandonment. In countries like India, extensive areas having sodic and partially reclaimed sodic lands remain prone to water stagnation in the post-monsoon months, adversely affecting winter season crops like wheat. Repeated instances of waterlogging are also known to cause secondary sodification in many areas, especially in the poorly drained lands underlain with sodic groundwater. Sodic soils suffering from waterlogging, with water table lying close to the surface (≤ 2 m), do not respond to gypsum and other amendments, suggesting the need for alternative approaches for reviving their productivity. Although subsurface horizontal drainage may lower the water table, lack of (natural) gravity outlets can render this technology unacceptable; pumped outlets are cost prohibitive for resource poor farmers. Such waterlogged sodic lands can be ameliorated by inverting the less sodic deeper soil profiles upside down which lowers the water table below a critical depth and improves the internal drainage. In this method, land shaping is done to create fish ponds and raised and sunken beds. In sunken beds, water table lies at ≈ 1 m depth resulting in reduced upward salt translocation. Cultivation of rice and water chestnut (*Trapa bispinosa*) and integrated rice-fish culture are the economically viable land use options for the sunken beds. Vegetable crops should preferably be grown on raised beds for higher returns (Verma et al. 2015).

In coastal salt-affected soils, intense rainfall, relatively flat topography, poor water sorptivity and lack of natural drainage restrict the downward movement of water such that regular irrigation even with marginally saline water (2 dS m^{-1}) would shortly cause salt accumulation. Fine-textured low-lying coastal lands rich in insoluble humic acid seem to be particularly highly vulnerable to waterlogging. Under such conditions, backwater flows may further reduce the efficiency of surface drainage for removing the excess water. Limited practical utility of both surface and subsurface drainage in coastal areas has enhanced the interest in other means of salt leaching. Although some practices such as deep ploughing, addition of sand/rice husk, continuous ponding of fresh water and vertical drainage may offer temporary relief, they suffer from one constraint or other limiting their widespread use. In some coastal saline areas (e.g. West Bengal, India), cropping intensity may be very low as a large proportion of the farmlands remain fallow due to excess water and salinity. Simple earth replacement techniques like farm pond and integrated rice-fish cultivation can be promising solutions for land use intensification under such conditions. Rainwater harvested in these structures not only reduces the soil salinity but also ensures ample availability of fresh water for irrigating the winter season crops. Farm ponds are developed by excavating ~20% of the soil from a depth of 3 m. Rainwater stored in these ponds can be used for round-the-year irrigation of crops grown on embankments. Besides fish rearing in the pond and crop cultivation on dykes, poultry and duckery can also be taken up for enhancing profits while recycling the resources among different components. In paddy-cum-fish model, trenches (3 m top width × 1.5 m bottom width × 1.5 m depth) are made around the farmland. Excavated soil is used for making dykes (1.5 m top width × 1.5 m height × 3 m bottom width) to prevent free flow of water from the field and harvesting more rainwater in the field and trench. While dykes are used to grow vegetables throughout the year, the rest of the farm area including trenches is used for integrated rice-fish culture (Mandal et al. 2013). These interventions can increase the cropping intensity from 114% to 186%, increasing the farm incomes (Mandal et al. 2017).

20.4 Plant-based Solutions

Most of the aforementioned solutions are essentially ‘reactive’ in nature as they intend to revive the productivity of salt-impaired lands by improving the root zone conditions. Contrarily, the ‘adaptive’ approach of improving the productivity of salt-affected soils consists in growing the salt-tolerant crops and cultivars. As mentioned previously, integrated use of amendments and salt-tolerant cultivars can save up to three-fourths of reclamation costs in sodic areas. Similarly, introduction of salt hardy cultivars can make it possible to produce acceptable yields in waterlogged saline lands. Evidently, crops and cultivars capable of enduring excess salts and related constraints can greatly minimize the use of amendments and fresh water for salt removal. There is evidence that in addition to producing stable yields several tree, shrub and grass species may bring out tangible improvements in soil quality over time. Several plant species gradually remediate the calcareous sodic soils by improving the dissolution of native calcite to release sufficient Ca^{2+} for removing the excess Na^{+} (Qadir et al. 2007).

20.4.1 Agroforestry Interventions in Sodic Soils

Many investigations have shown that cultivation of agroforestry species could be a feasible intervention for generating additional returns while simultaneously improving the quality of degraded salty lands lying barren for one reason or other. This approach may particularly be well suited for the revegetation of public and community lands. Depending on magnitude of salt stress, trees and other species can be grown with or without amendments. For example, gypsum application considerably improved the biomass production in mesquite (*Prosopis juliflora*) trees in a highly sodic soil (pH, 10.4; ESP, 90) compared to the trees grown without gypsum treatment (Singh et al. 1989). This indicated that soil pH and ESP may sometimes be too high to suppress the growth of even salt-tolerant species necessitating the amendment use for partly ameliorating the root zone soil. Once established, trees do not need much care and slowly reduce the soil pH and salinity coupled with increase in soil organic carbon (SOC) and nutrient levels ascribed to rhizospheric excretions and nutrient additions through litter fall and root decomposition. Integration of subsidiary crops (e.g. grasses) may not always be compatible with the main (tree) component but may result in faster reclamation. According to Singh (1995), intercropping of Kallar grass decreased the growth of mesquite trees, but soil reclamation was relatively better and quicker in the mixed tree-grass plots than those having trees only. Similarly, Kaur et al. (2000) reported much higher microbial biomass carbon, SOC and N mineralization rates in *Acacia*, *Eucalyptus* and *Populus*-based agri-silvicultural systems compared to single species stands and rice-berseem rotation in a sodic soil. Soil carbon was 11–52% higher in integrated tree-crop systems than other land use systems. Singh et al. (2011) observed that *Prosopis juliflora*, *Acacia nilotica* and *Casuarina equisetifolia* cultivation resulted in significant reductions in soil pH, EC and ESP and marked increases in SOC and available NPK contents than control soil ($pH_{2,}$ 8.8–10.5; ESP, 85–92). Batra et al. (1997) and Kumar et al. (1994) found that salt-tolerant Kallar grass grown with or without gypsum application led to gradual reductions in pH and ESP of degraded sodic soils ascribed to *in situ* biomass decomposition and root-mediated improvements in soil quality. Dagar et al. (2004) observed that aromatic grasses such as palmarosa (*Cymbopogon martinii*) and lemon grass (*C. flexuosus*) also exert ameliorative effects in sodic soils with only slight reductions in herbage and essential oil yields.

Factors like soil pH and ESP, tree planting and management practices, climatic conditions, irrigation water quality and the expected economic returns greatly determine the success of a particular agroforestry intervention. For example, mesquite trees planted in gypsum and FYM -ameliorated auger-holes showed better establishment and growth than those planted in trenches in a highly sodic soil (ESP, 94) (Singh et al. 1988). Similarly, biomass production by mesquite trees in a strongly alkali soil (pH, 10.3) was much higher when planted in 90-cm-deep auger-holes than in shallow (30 cm) trenches and pits. Saplings planted in auger-holes produced well-developed roots (≈2.5 m deep) penetrating the hard subsurface calcite pan. In arid and semiarid regions, low availability of fresh water and salinity may sometimes reduce tree survival and establishment emphasizing the need for rainwater harvesting for supplemental irrigation, especially during the initial few years after planting. It is seen that some agroforestry trees having higher reclamation efficiency may not always be preferred by the land owners due to their nonremunerative nature. For example, while *Acacia*-based systems outperform *Populus*- and *Eucalyptus*-based systems in improving sodic soils, net returns are much higher in the latter two systems (Singh et al. 1997).

20.4.2 Biodrainage for Preventing Salinity Build-up

Biodrainage (i.e. biological drainage) refers to the planting of salt-tolerant trees for arresting salt accumulation and lowering of watertable in waterlogged lands. Trees having both salt tolerance and a high transpiration rate are preferred for this purpose. Biodrainage being a preventive measure, however, provides the best results when tree planting coincides with the start of irrigation water use in a particular canal command. This intervention may be of little use in lands facing moderate to high levels of waterlogging and salinity. In addition to preventing the salinization of irrigated lands, perennial trees and shrubs are also advocated for arresting the rise of saline groundwater in dryland areas. Nonetheless, shallow saline water tables in discharge zones often hinder such revegetation plans (George et al. 1999). In comparison to most of the annual crops having a shallow root system, tree roots penetrate deeper (>2 m) in the soil rapidly transpiring the groundwater and thus decreasing the water table by 1–2 m over a period of 3–5 years. Root system in most of the perennial trees is dimorphic, i.e. consisting of surface and sinker components. In contrast to the horizontally spreading surface roots, sinker roots penetrate vertically to 10 m depth or more. Together, they form an integrated conduit in the soil that causes upward hydraulic redistribution of the deep soil water (Devi et al. 2016).

Tree species vary considerably in their biodrainage capacity, and those having higher water removal efficiency are preferred for field applications. In India, for example, *Eucalyptus tereticornis* trees are generally recommended for biodrainage. Three- to 4-year-old *Eucalyptus* trees can bio-drain over 5000 mm of water from nonsaline, moderately deep (≈1.5 m) water tables. Relatively shallow (≈1 m) or deep (≈ 2 m) water table depths reduce the trees' biodrainage capacity that also declines with increase in the salinity of groundwater. However, at salinities as high as 12 dS m^{-1}, *Eucalyptus* trees can remove ≈50% of the water compared to that under nonsaline conditions. *Eucalyptus tereticornis* trees could control water table rises up to 1.95, 3.48, 3.76 and 3.64 m in first, second, third and fourth years of planting, respectively. After tree planting, salinity up to 45 cm depth did not exceed 4 dS m^{-1} even at saline (12 dS m^{-1}) water table depth of 1 m. Similarly, bamboo (*Bambusa arundinacea*) plants could control water table rises up to 1.09, 1.86, 2.46 and 2.96 m in first, second, third and fourth years of growth, respectively (Chhabra and Thakur 1998). Strip plantations of *Eucalyptus tereticornis* on ridges in north-south direction not only lowered the water table by 0.85 m in 3 years but also sequestered 15.5 Mg ha^{-1} carbon during the first rotation of 64 months. B:C ratio of the first rotation of strip plantations was 3.5:1. Wheat yield in the tree interspaces was over threefold higher than in adjacent waterlogged soils (Ram et al. 2011). These observations suggest that trees extracting saline water from deeper layers can control water table rise and the formation of waterlogged saline lands.

20.4.3 Disposal of Sewage Effluents in Tree Plantations

Generation of huge amounts of domestic and industrial wastewater in rapidly growing cities across the world is increasingly becoming a major environmental concern. Existing wastewater treatment facilities in many countries are grossly inadequate such that large quantities of untreated effluents are directly discharged into water bodies and on potentially arable lands. Use of untreated wastewater in irrigation has also increased considerably in many areas for producing high-value horticultural crops, albeit at the cost of sodicity and heavy metal build-up in soils because of moderate to high SAR values of such effluents. Conventionally, sewage is collected through a network of sewerage systems and the subsequent transport to a centralized treatment plant. However, it is a resource-intensive practice suggesting the need for encouraging decentralized wastewater treatment using environment-compatible technologies (Parkinson and Tayler 2003). Properly treated effluents can be used in pisciculture and irrigation of perennial tree crops used for fuel and timber (Kamyotra and Bhardwaj 2011). Certain agroforestry plantations are considered a safe sink for disposing the wastewater. Fast-growing, short rotation tree species such as *Eucalypts*, *Populus* and *Salix* besides remediating the wastewater-contaminated soils can also provide socio-environmental benefits in terms of fuel, timber and carbon sequestration (Rockwood et al. 2004). Nonetheless, similar to other crops, different design and management factors like rotation period, water and nutrient needs and tolerance to salinity and heavy metals greatly influence the ability of trees in wastewater removal. For the best results, location- and tree-specific irrigation methods and water quality guidelines need to be developed. Wastewater-irrigated tree groves are often much more vigorous and productive than their freshwater-irrigated counterparts, a fact attributable to higher nutrient content of wastewater. However, environmentally safe irrigation methods are needed to ensure that nutrient additions through wastewater match the plant needs so that excess nutrients do not leach to the groundwater posing pollution risks (Braatz and Kandiah 1996). In India, ICAR-CSSRI, Karnal, has pioneered the work for the sustainable disposal of wastewater in tree plantations. In this practice, popularly called as ‘Karnal Technology’, trees are planted on 1-m-wide and 50-cm-high ridges, and the untreated sewage is disposed in furrows. The amount of the sewage effluents to be disposed of depends upon tree age, plant species, agroclimatic conditions, soil properties and the quality of effluents. Total sewage discharge is regulated in a way that it could be consumed within 12–18 h so that no water stands in the trenches.

20.4.4 Fruit Crops

Relatively longer gestation period of and low returns from agroforestry models have increased the interest in other high-value land use options in salt-affected soils. Many studies have been conducted to develop suitable interventions for raising fruit crops in saline and sodic soils as a ‘low investment, high-income option’. Workable technologies for improving the salt tolerance in fruit crops include use of salt-tolerant rootstocks, improved planting techniques and irrigation management. Dagar et al. (2001) evaluated ten different fruit species in a highly sodic soil (pH 10.0) using auger-hole and pit methods of planting and 5–20 kg of gypsum as amendment. Based on long-term observations, Indian jujube (*Ziziphus mauritiana*), jamun (*Syzygium cumini*), guava (*Psidium guajava*), aonla (*Emblica officinalis*) and karonda (*Carissa congesta*) were adjudged to be the promising fruit species for such soils. Saxena and Gupta (2006) observed that litchi cv. Rose Scented established well in semi-reclaimed sodic soils (pH, 8.5–9.0) when planted in sand and FYM (20 kg pit^{-1})-treated pits. Drip irrigation further improved plant growth by overcoming structural problems and low permeability. Tomar and Gupta (1985) reported that nearly half of the aonla trees withstood the rigours of waterlogging and salinity when planted on ridges (EC$_e$ 8–12 dS m^{-1}) but did not survive when raised in the subsurface pits, apparently due to very high salinity (EC$_e$ up to 18 dS m^{-1}). Recently, Singh et al. (2018) observed that guava and bael plants showed profuse growth when grown on raised beds (~2 feet) and irrigated with marginally saline water (3–4 dS m^{-1}) in a waterlogged saline soil. Further increase in irrigation water salinity, however, caused severe injury and plant mortality. These observations tend to show that even simple-to-do interventions can be of considerable help in raising the salt-sensitive plants in salt-impaired lands.

20.4.5 Salt-tolerant Crop Cultivars

The foregoing discussion leads to the conclusion that some of the best salinity management practices (e.g. gypsum-based package and SSD technology) may sometimes be difficult to implement. This implies the need to develop alternative solutions capable of providing acceptable economic returns from the salt-affected soils. There is critical evidence that salt-tolerant cultivars (STCs) are a cost-efficient means of salinity management. Some of the advantages of using STCs over popular yet salt-sensitive cultivars include reduced or no use of amendments, low leaching requirement and assured harvests in situations where salt-sensitive cultivars even fail to germinate and grow. Importance of high-yielding STCs is perhaps best illustrated by rice, a salt-sensitive plant inefficient in controlling the influx of Na^+ through the roots, where high-yielding STCs can provide a yield advantage of 1.5–2 Mg ha^{-1}. Despite these benefits, development and commercial release of salt-tolerant cultivars has progressed rather slowly due to complex inheritance of salt tolerance and the effects of environmental factors on character expression. In India, decades of concerted efforts have led to the development of high-yielding salt-tolerant cultivars in rice, wheat, mustard and chick pea which are currently being grown over a large salt-affected area. Several potential genetic stocks have also been developed for the use as parents in future selection and hybridization programmes. Salt-tolerant cultivars of rice (Sharma 1986) and wheat (Sharma 1991) tend to maintain a low leaf Na^+/K^+ ratio. Additionally, such STCs also exhibit higher leaf chlorophyll, starch and proline contents than both semi-tolerant and sensitive ones (Rao et al. 2013). Salt-tolerant Indian mustard cultivars such as CS 52 and CS 54 produce $\approx$20% more seed yield and $\approx$36% more oil yield in saline (EC$_e$ up to 9 dS m^{-1}) and sodic (pH up to 9.3) soils than high-yielding varieties like Varuna and Kranti (Sharma and Sinha 2012).

Of late, molecular techniques have become an integral part of cultivar evaluation and screening trials. Identification of genes and molecular traits underpinning salt tolerance can ultimately pave the way for their incorporation into popular salt-sensitive cultivars through conventional and marker-assisted breeding approaches. It is also seen that some factors may hinder the adoption of STCs by the farmers. This has led to farmer participatory varietal trials for developing high-yielding STCs best suited to the location-specific needs. Such a cultivar evaluation programme recently culminated into the release of salt-tolerant rice cv. CSR 43 for commercial cultivation in sodic areas of central Indo-Gangetic Plains (Singh et al. 2014).

20.5 Improved Irrigation Methods

Globally, irrigated agriculture consumes ~75% of the total available water, while the remaining is utilized by the industrial (20%) and municipal (5%) sectors. Factors like burgeoning human population, pervasive land use, urbanization and industrialization have intensified the competition for the use of prime cropland manifold. Climate change impacts (high temperature, erratic rainfall and reduced river flows) are dealing a severe blow to freshwater supplies in many areas of the world. These inevitable changes in land and water use dynamics imply that agricultural production will have to increasingly depend on poor soils and waters. Currently, farmers in several areas have no other option but to utilize low-quality water in irrigation and soil reclamation. Under such conditions, a well-thought-out strategy including integration of low water-requiring crops in the existing cropping systems, adoption of salt-tolerant cultivars, use of amendments and water use-efficient micro-irrigation techniques has become absolutely essential.

Maintaining the root zone salt levels below crop salt tolerance threshold by leaching is a prerequisite for stable agricultural production in salty lands. Water in excess of crop evapotranspiration (ET_c) requirement (leaching requirement) needs to be applied either regularly or occasionally to leach the salts below the root zone. However, leaching is feasible only in well-drained lands as shallow (saline) water tables besides restricting the downward salt flux also accelerate upward salt movements (Ayars et al. 2012). Crop water use efficiency and salt accumulation in soil are governed by many factors, the method of irrigation being one such major factor. While surface methods of irrigation like flood and furrow facilitate even spread of water on land surface and thus quicker salt leaching, they come at the cost of heavy water use, often increasing the risks of deep percolation and waterlogging (Ali 2011). Consequently, sprinkler and drip methods of irrigation are increasingly being used for the uniform application of water while curtailing the water wastages and ensuring adequate leaching, especially in areas having poor drainage. However, high evaporative losses and rapid development of salt toxicity symptoms in crops are major limitations to the use of sprinkler method using saline water. Quite the contrary, these problems are not encountered with drip irrigation. Besides no risk of foliar injury, wetted area around the emitters having relatively higher root density is constantly leached out of salts, and high-frequency applications ensure constant soil water content (Hanson and May 2011). Some additional benefits of drip irrigation include higher crop water use efficiency, reduced weed infestations and better crop yields and quality.

Deficit irrigation can be another potential technique for augmenting the irrigation water productivity. In this method, irrigation is applied below ET_c. It is particularly suited to perennial fruits, nuts and vines in semiarid and subhumid areas where annual rainfall can partly fulfil the crop water needs during critical stages (Fereres and Soriano 2007). In arid areas, however, deficit irrigated soils will shortly witness prohibitive levels of salts with the use of fresh water. Deficit irrigated (EC_{IW} 1 dS m^{-1}) mandarin (*Citrus clementina* cv. 'Orogrande') orchard soils consumed ~15% less water than conventional method of irrigation without any significant reduction in fruit yield, but root zone salinity considerably increased after 3 years (Mounzer et al. 2013). Partial root zone drying (PRD) is another similar technique in which only half of the root system is irrigated, while the rest half is kept dry. Interest in PRD grew because of the difficulties faced in maintaining precise soil water balance through deficit irrigation. Alternate partial root zone irrigation (APRI) and fixed partial root zone irrigation (FPRI) are the two variants of PRD technique. As the names suggest, alternate irrigation is done on both sides of the root zone in APRI, while FPRI consists in applying water on only one (fixed) side of the root zone. Experimental evidence suggests that PRD can help reduce irrigation water use considerably in fruit crops like peach, olive and grapes. The drying roots of PRD trees synthesize abscisic acid that modulates stomatal conductance in a manner that minimizes water loss through transpiration but does not affect leaf turgidity and carbon assimilation (Sadras 2009; Sepaskhah and Ahmadi 2010).

20.6 Sustainable Intensification in Reclaimed Areas

While secondary salinization continues to affect irrigated lands, resodification and resalinization problems in the reclaimed areas are increasingly being reported. Resodification refers to the reappearance of sodic patches in a sizeable area of reclaimed sodic soils. Resalinization of ameliorated saline lands ascribed to climate- and human-induced redistribution of salts describes the reaccumulation of salts over the surface. Reversion of reclaimed lands to the pre-reclamation state implies that efforts made for reviving the soil productivity were in vain. It seems that croplands located near canals and particularly those having a hard subsoil pan, drainage congestion and shallow water table are extremely sensitive to these problems (Yadav et al. 2010). Evidence is also mounting that intensive irrigation and agrochemical use have also led to many second-generation problems such as groundwater depletion and contamination, loss of soil organic carbon and nutrients, pest and disease outbreaks and crop residue burning in many irrigated areas of the world and can have wide-ranging ramifications for the food, environmental and economic security of the local people. The options suggested for containing these problems include conservation agriculture practices and integrated farming.

Conservation agriculture (CA) practices along with the substitution of water guzzling commodities like rice with low water-requiring coarse grains, oilseed and legume crops can help achieve sustainable crop intensification in many irrigated around the globe. Gathala et al. (2014), by comparing different cropping system scenarios with the farmers' practice, observed that resource conservation technologies like reduced tillage, residue management, crop substitution and innovative crop establishment methods were highly efficient in enhancing the system productivity and profitability. Direct-seeded rice with residue retention provided equivalent or higher yield with 30–50% saving in irrigation water use than farmers' practice of puddled transplanted rice. Replacement of rice with zero-tillage maize gave similar profits while saving ~90% irrigation water. Choudhary et al. (2018) observed that CA-based sustainable intensification of maize-wheat systems was a better alternative to rice-wheat system of Indo-Gangetic Plains; it could save 79% of irrigation water while increasing the crop and water productivity by 12% and 145%, respectively, along with high (34%) economic benefits. Tirol-Padre et al. (2016) found that a transition from conventional to CA-based practices in rice crop can reduce global warming potential (GWP) for rice by 23% or by 1.26 Tg CO_2 eq y^{-1}. An intensive CA-based rice-wheat and maize-wheat system reduced GWP by 16–26% or by 1.3–2.0 Tg CO_2 eq y^{-1} compared with the conventional rice-wheat system mainly due to reduction in diesel and electricity consumption. An integrated crop-fish-livestock model has been standardized for the small landholders (2 ha land area) in reclaimed sodic areas. This model consists of field and horticultural crops, fish culture, cattle, poultry and beekeeping. Available resources can efficiently be recycled among different components for reducing the environmental footprints and lessening the production costs. Integration of different components ensures higher and regular incomes to the farm families who otherwise derive incomes from rice and wheat crops only. Generation of round-the-year employment and nutritional security of farm families are the added benefits of this model (Sharma and Singh 2015).

20.7 Managing Seawater Intrusion in Coastal Areas

Seawater intrusion (SWI) refers to the ingress of salty seawater into coastal aquifers which constitute a major source of freshwater supply, especially in arid and semiarid regions. Most of the coastal areas being densely populated zones remain highly vulnerable to the constraints imposed on groundwater utilization. As the problem of seawater ingress intensifies, freshwater aquifers in the immediate vicinity of the coast may no longer remain usable leading to their abandonment (Bear et al. 1999). Although both natural and human processes affect the rate of salt ingress, climate change-induced sea-level rise has recently emerged as a major driver of SWI. According to the Intergovernmental Panel on Climate Change (IPCC) projections, sea level can rise by at least 110 mm and even up to 880 mm in worst-case scenario by the end of the twenty-first century, accelerating the inland migration of the mixing zone between fresh and saline water (cited in Werner and Simmons 2009). Available evidence suggests that excessive groundwater pumping alters the natural flow systems in ways that prove conducive to seawater intrusion and groundwater degradation (Pulido-Leboeuf 2004). While recurring episodes of deficient rainfall coupled with population growth increase the stress on coastal aquifers resulting in their overexploitation and the accompanying rise in salinity (Werner 2010), duration and intensity of groundwater pumping remain the dominant factors governing the rate of salt intrusion (El Moujabber et al. 2006). High sensitivity of coastal aquifers to SWI is ascribed to 'upconing' – the process by which saline water underlying fresh water moves upward due to continued pumping. In extreme cases, pumping may have to be stopped to prevent further deterioration in water quality. Upconing occurs because fresh water floats over the denser saline water as a thin layer; with a unit drop in fresh water, saline water may rise by up to 40 units. It is due to this reason that careful skimming of freshwater layer instead of pumping is recommended for the productive management of coastal aquifers (Dhiman and Thambi 2010).

Depending on whether hydraulic gradient slopes toward the sea or the land, SWI is categorized into 'passive' and 'active' categories, respectively. As hydraulic gradient slopes toward the land and forces caused by density differences and fresh groundwater flow act in the same direction, active SWI results in rapid aquifer salinization (Badaruddin et al. 2017). Uncontrolled mixing of seawater into freshwater aquifers can have a debilitating impact on soil health, agro-biodiversity and crop production. In areas where contaminated groundwater is used for irrigation, soil salinity and alkalinity steadily increase, but impacts usually decrease with increase in distance from the shoreline. In soils and groundwaters facing seawater-induced salinity, higher nitrate nitrogen levels may also frequently pose an additional problem with dissolved nitrate levels exceeding the permissible limits for drinking and irrigation. Excessive applications of nitrogen fertilizers, use of wastewater in irrigation and movement of contaminants in areas of high hydraulic gradients within the drawdown cones could be the likely causes behind elevated nitrate concentrations in soils and groundwater (Zghibi et al. 2013). In recent decades, increased incidence of SWI has been reported from several parts of the world due mainly to population growth and excessive groundwater withdrawal. Seawater intrusion has rendered about 2500 km^2 land area saline around the Bohai Sea in the northern part of China (Shi and Jiao 2014). Heavy groundwater pumping for sugarcane cultivation since about middle of the twentieth century has led to rapid SWI in many coastal areas of Queensland, Australia (Narayan et al. 2007). SWI is increasingly being seen as a major environmental threat to the coastal aquifers in several parts of the Mediterranean Basin (Recinos et al. 2015). Seawater ingress has also been observed in many parts of India including Gujarat, Tamil Nadu and Lakshadweep (Dhiman and Thambi 2010). In Gujarat, having the longest coastline (~1600 km) in India, SWI due to intensive groundwater extraction and decreased aquifer recharge is becoming a serious concern in about a dozen districts flanking the Arabian Sea. Excessive fluoride and nitrate levels in groundwater have also been detected in many areas (Krishnan et al. 2007).

Several solutions have been suggested for preventing the mixing of salty seawater into coastal aquifers by maintaining the groundwater levels. Construction of large recharge pits and surface spreading of water can partly replenish the groundwater. Nonetheless, these interventions may be cost prohibitive and inefficient in excessively pumped unconfined aquifer systems (Narayan et al. 2007). Injection wells or subsurface barriers can also be suitable interventions for preventing SWI and improving water quality in some coastal areas (Allow 2012). The location and penetration depth of recharge wells and subsurface flow barriers are the major factors controlling SWI in unconfined coastal aquifers. For example, injection of recharge water at the toe of saltwater wedge proves very effective in deterring SWI. Similarly, more effective saltwater repulsion can be achieved when barriers are placed deeper and closer to the coast (Luyun Jr et al. 2011). Despite proven benefits, ample precaution is necessary while employing such measures. One study conducted in a coastal area of the Mekong River Delta, Vietnam, where sluices for controlling SWI were constructed and operated in a phased manner, revealed positive impacts in upstream areas but adverse effects in downstream parts. While canal water salinity declined rapidly upstream (western part) of sluices leading to increased rice production, reduced supply of brackish water adversely affected brackish water shrimp farming in the eastern part, reflecting the high sensitivity of coastal lands to the external interventions (Tuong et al. 2003).

20.8 Conclusions and Future Perspective

Sustainable management of land and water resources continues to be one of the top priorities of global developmental agencies and the national governments. This case is perhaps best illustrated by the recently unveiled ‘Sustainable Development Goals’ (SDGs) placing a critical emphasis on sustainable soil and water management for combating land degradation and desertification. Excess salts in soil and water are known to cause physical and chemical degradation of millions of hectares of potentially arable lands across the world. Salt-induced land degradation is by no means a new problem; salinity is known to swallow productive farmlands and cause human misery since ancient times. Nonetheless, the problem has attained alarming proportions in the past few decades in many irrigated basins like the Mediterranean Basin, the Indo-Gangetic Plains and Murray-Darling Basin. Several efficient solutions have been developed for reclaiming and managing the salt-affected soils and poor-quality waters. While some of salinity management technologies have gained immense popularity, others largely remain underexploited reflecting the need for continual refinements for making them compatible with the location-specific needs.

Twin menaces of waterlogging and salinity are essentially regional problems implying that instead of site-specific experiments focus should be on regional modelling studies to draw valid conclusions on the nature and extent of the problem and to devise appropriate benchmarks for the cost-effective management of salt and water balances. Research on potential alternative amendments such as nano-based polymers, elemental sulphur, municipal solid waste compost and marine gypsum needs to be prioritized for reducing the dependence on mined gypsum. Simple land shaping interventions capable of reviving the productivity of waterlogged salty lands need to be demonstrated on a large scale for convincing the policymakers and farmers for their commercial adoption. Molecular techniques need to be harnessed for accelerating the development of multi-stress-tolerant crop cultivars. Resource conservation technologies have become the need of the hour for safeguarding the reclaimed soils from resodification and resalinization. In the scenario of climate change, agroforestry-based agricultural systems are not only sustainable and assure livelihood security to marginal farmers but also mitigate climate change through carbon sequestration and improvement in environment.

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Coastal Saline Soils of Gujarat (India): Problems, Reclamation Measures and Management Strategies

21

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and Divyang Waghela

Abstract

Soil salinization is a serious global concern because it reduces the potential productivity and use of land and water resources. In coastal regions, salinization may lead to degradative changes in the chemical composition of natural water resources, for domestic, agriculture, and industrial sectors, loss of biodiversity, taxonomic replacement by halo-tolerant species, loss of fertile soil, collapse of agricultural and fishery industries, changes in local climatic conditions, and creating health problems, thus affecting many aspects of human life and posing major hindrance to the economic development of the region. Gujarat state shares the longest coastal line in the country, i.e., 1600 km, out of which Kutch and Saurashtra are facing salinity ingress far and wide on the 1125-km-long coastal belt engulfing 779 villages with a population of 1.33 million. To address the severe problem of water and land salinity in the coastal regions, the Gujarat State Government appointed two High-level Committees (HLC 1 and HLC 2) in the 1970s and 1980s. Various measures involving engineering, agriculture, forestry, and social and legal aspects have been suggested as a part of an integrated approach to reduce the water and land salinity problem and improve conditions in the salinity-affected areas. It has become mandatory to develop location-specific programs on water allocation based on soil, climate, water, and crop

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parameters, with minimal dependence on groundwater abstraction with overall target to increase the water productivity and cropping intensity while simultaneously conserving the ecosystem. In the present paper, aspects related to coastal salinity issues, measures undertaken as per the HLCs, works undertaken by other agencies, and some agro-interventions ideal for coastal saline soils with more emphasis to Gujarat are elaborated.

Keywords
Coastal salinity · Gujarat · High-level committee · Sea ingress · Groundwater recharge · Agro-interventions

21.1 Introduction

Soil salinity, an environmental problem, is the product of complex interaction of many variables which lessen the current and/or potential capability of soil to produce goods and services. In general, the subsequent changes in land-use patterns mainly due to agricultural intensification processes together with many unfavorable natural conditions have accelerated soil salinity problems in many parts of the world. While the problem has caused immense loss to agriculture, particularly in irrigation command areas and in coastal areas, its further spread indicates a grim picture. It is reported that about 6.73 Mha land is salt-affected in India (NRSA and Associates 1996) of which 2.22 Mha is present in Gujarat state (Fig. 21.1). The problems of environmental degradation in Gujarat state are as diverse and complex as the ecological fabric of the state. While some of the problems are widespread and operate over the long term, the others are mainly localized and more intensive in their impacts. Soil and water salinity problems are essentially multi-sectorial and are complex in nature. Vast areas are in imminent danger of turning barren, and production and productivity have simply declined due to secondary salinization. Soil salinity problems are further compounded where the groundwater is highly

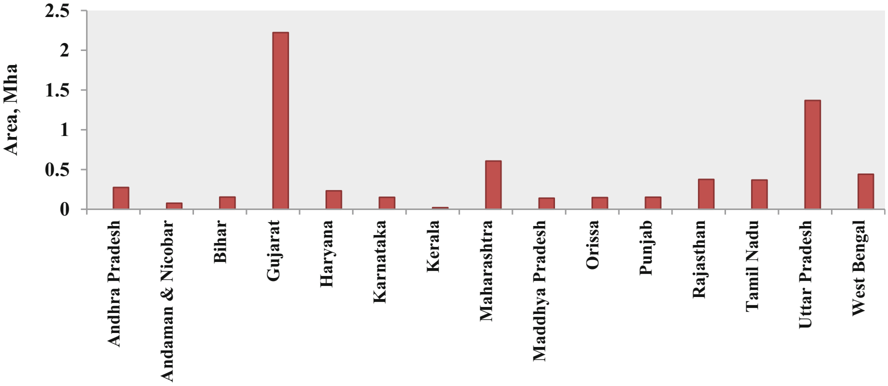

Fig. 21.1 State-wise distribution of salt-affected soils in India (Mha), area in India = 6.73 Mha

saline, and such areas by and large remain barren for want of economically feasible technological interventions, thereby affecting the livelihood of the farmers.

21.2 Coastal Salinity Problems in India

Coastal ecosystem is generally endowed with very delicately balanced resources that sustain substantial human and animal population. The resources, if properly managed, can contribute significantly to the GDP of the country. The coastal soils exhibit a great deal of diversity in terms of climate, physiography, and physical characteristics as well as rich stock of flora and fauna. These are dynamic systems, undergoing changes in form and processes in time and space in response to oceanographic conditions and geomorphic features. India has a long coast line of 8129 km spread (Fig. 21.2) over as many as nine states, two union territories, and two island ecosystems and two archipelagoes (Fig. 21.3).

As such the country has a vast area under coastal agroecosystem with very low productivity, having high intensity of population and inhabited by the poorest farmers of the world. At global level, about 40% of populace lives along the 312,000-km-long coastline. Coastal areas in India and elsewhere are *by and large* heavily populated. Natural calamities like cyclones, storms, tsunami, sea ingress, and tornado occur very frequently in the area causing enormous losses to the lives and properties of the people. The coastal region is likely to face severe challenges in the future due to rise in sea level resulting from global warming. Planning for effective and sustainable development of this ecosystem requires adoption of integrated approach to soil and water management in the first place and, through it or otherwise, necessary measures to conserve the ecology. The major problems encountered in coastal soils are:

- These lands are subjected to the influence of tidal waves and periodical inundation by tidal water.
- Shallow water table enriched with salt contributes to increase in soil salinity during winter and summer months.
- Heavy rainfall resulting in excess water during *kharif* (rainy) season.
- Poor surface and subsurface drainage conditions.
- Lack of good-quality irrigation water and acute salinity during *rabi*.
- Poor socioeconomic conditions of the farming community limiting introduction of high-investment technologies.

21.2.1 Soil Salinity Buildup

Salinity buildup in soil is due to saline seawater ingress through the following processes: (a) excessive abstraction of groundwater from the coastal plain aquifers, (b) tidal water ingress, (c) relatively less recharge, and (d) poor land and water management.

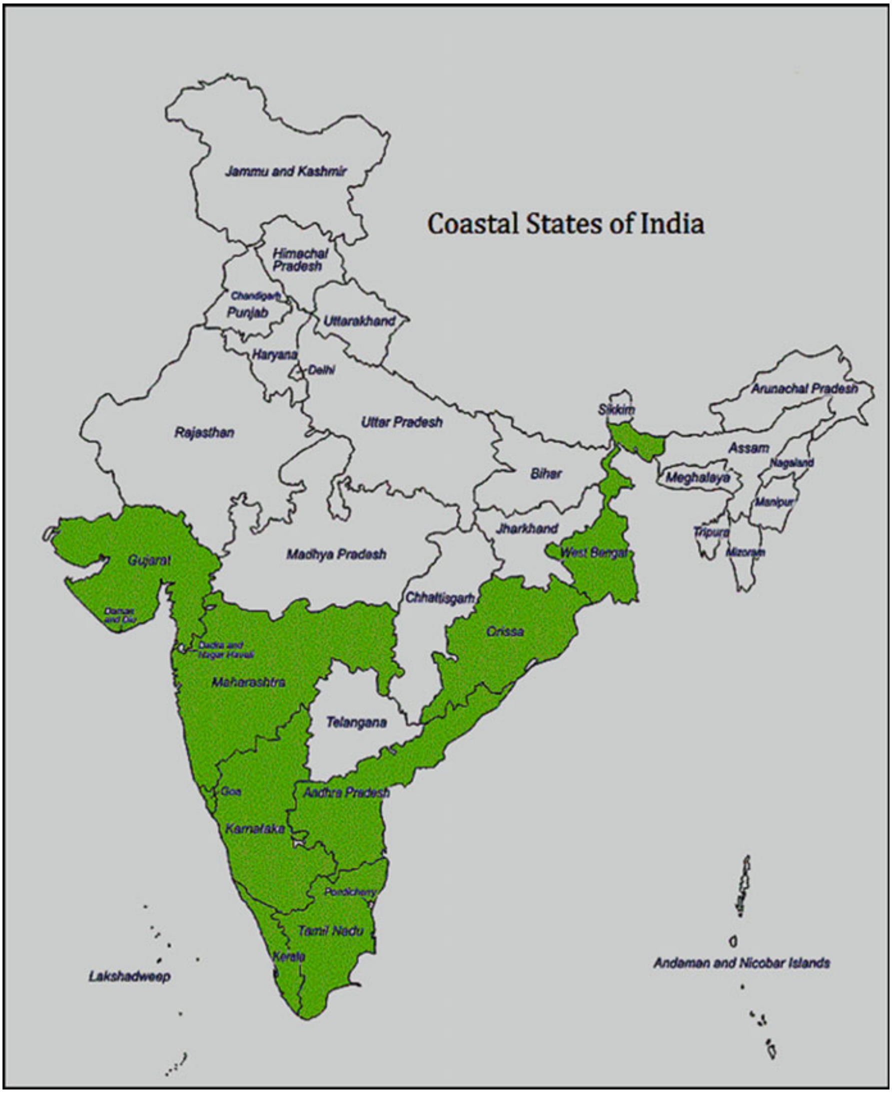

Fig. 21.2 The coastal states and union territories of India

21.3 Seawater Intrusion and Progressive Coastal Land Salinization

Many coastal communities rely on groundwater for meeting their potable water requirements. However, indiscriminate large-scale pumping of groundwater may lead to progressive saltwater intrusion into the freshwater coastal aquifer system that

Fig. 21.3 Coastal belt of the Indian subcontinent

ultimately renders the groundwater unfit for human consumption and other uses. Irrigation of crops using saline water may also result in degradation of soil and widespread destruction of fertile coastal lands. During extended droughts, decreased river flow allows the saline water to migrate up the estuary to inland areas that may further contribute to land salinization (Fig. 21.4). In addition, rise in sea level will also cause seawater to migrate upstream and inundate low-lying areas. Coastal land salinization and saltwater ingress are major hazards encountered along the Indian coast hampering socioeconomic growth in the coastal states and the economy of the country as a whole.

Fig. 21.4 Highly saline tract in the Bhal area (Khambhat)

21.3.1 Lateral Intrusion of Seawater

Lateral seawater intrusion occurs in coastal zones because of interaction between the seawater and hydrologically connected coastal aquifers. Under natural undisturbed conditions, a seaward hydraulic gradient exists in the aquifer with freshwater discharging into the sea. The increased salt water flow in from the sea and a landward thinning "saltwater wedge" develops beneath the lighter freshwater. The resulting saltwater-freshwater interface is not a firm boundary but exists as a transition zone reflecting changes in salinity. Lateral seawater intrusion in coastal areas may be enhanced by surface water bodies connected to the sea, such as estuaries and rivers (greatly increasing the coastline length). Pumping from coastal wells can draw salt water downward from such surface sources of saline water. This type of intrusion is usually more local in nature with a potential to contaminate portions of the aquifer near the river.

Overexploitation of groundwater has rendered it vulnerable to sea intrusion in different pockets mainly in Saurashtra region. Saltwater intrusion occurs horizontally as the saline water slowly pushes the fresh inland groundwater landward and upward. The cause can be both natural (due to rising sea levels) and anthropogenic (abstraction of freshwater). Pumping from coastal wells can also draw salt water downward from surface sources such as tidal creeks, canals, etc. Options for control of seawater ingress into aquifers include (i) modification of groundwater pumping and extraction patterns, (ii) artificial groundwater recharge, (iii) injection barriers, and (iv) subsurface barriers and tidal regulators, check dams, and reservoirs (Sen et al. 2012; Gururaja Rao et al. 2012, 2013, 2014a). However, for an effective and long-term sustainable solution to the problem of seawater intrusion into the groundwater, it is vital to develop location-specific optimization methods and models to identify suitable locations of the pumping wells and rates of withdrawal of the groundwater. Studies carried out by CSSRI through artificial groundwater recharge (Gururaja Rao et al. 2014a) and the efforts by the Gujarat State Land Development Corporation Ltd. (GSLDC) (Gururaja Rao et al. 2012, 2013) have paid dividends.

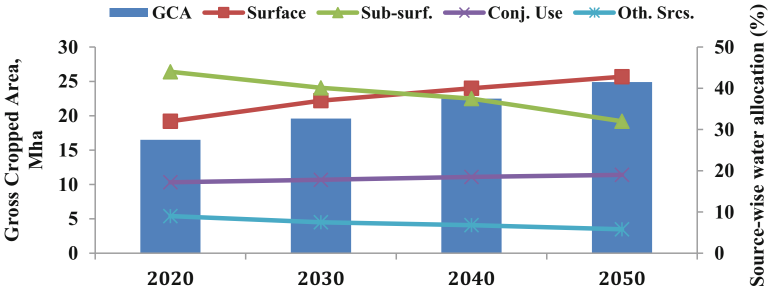

Fig. 21.5 Source-wise water allocation with respect to the total amount of irrigation water and the gross cropped area during the coming four decades in the coastal areas of India (Source: Sen et al. 2012)

21.3.2 Irrigation Water Resources in the Region

In order to have an appropriate coastal development by maintaining the water consumption to sustainable levels, the technological development should focus on artificial recharge of the aquifer, recycling of water, desalinization of seawater, improved irrigation water management practices, and use of marginal/poor-quality water. Thus, it is mandatory to develop location-specific programs on water allocation based on soil, climate, water, and crop parameters, with minimal dependence on groundwater abstraction with increasing reliance on other means like artificial recharge of the aquifer, recycling of water, and conjunctive use strategies. Sen et al. (2012) indicated a stepwise increase in water-use efficiency under different modes along with suggested increase in cropping intensity from 150% to 225% during 2020–2050 (Fig. 21.5). Field water balance model has been used to estimate surface water storage opportunities which should gradually dominate over groundwater use for stability of the coastal plain.

21.4 Scenario in Coastal Gujarat

The Gujarat state shares the longest coast line in the country, i.e., 1600 km, out of which Kutch and Saurashtra cover about 1125 km (Fig. 21.6) where seawater ingress has adversely affected the groundwater (Gururaja Rao et al. 2013). On an average 0.5–1.0 km distance from the coastline is affected by seawater ingress every year. A total of 16 coastal districts, covering ~ 68% area of the state and comprising ~58% of its dynamic groundwater resource, are adversely affected. These include the coastal districts, namely, Kutch, Morbi, Jamnagar, Devbhoomi Dwarka, Porbandar, Junagadh, Gir Somnath, Amreli, Bhavnagar, Anand, Ahmedabad, Vadodara, Bharuch, Surat, Navsari, and Valsad, besides the union territory of Daman (Daman and Diu). Thus, about 5- to 7.5-km-wide strip of the inland area has been

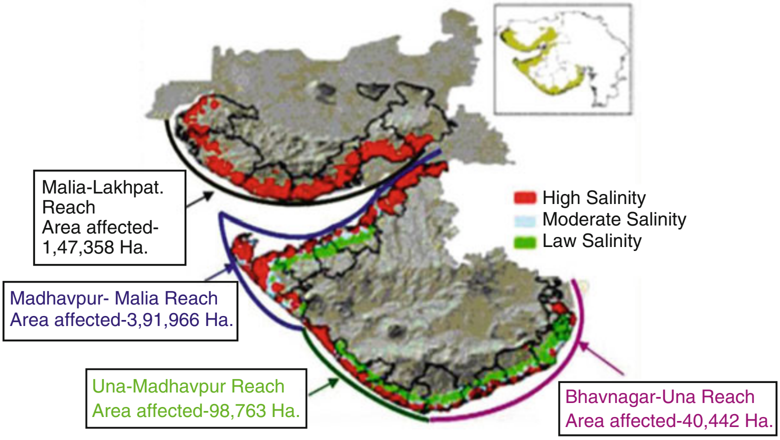

Fig. 21.6 Area affected by salinity ingress in Gujarat state

rendered saline till now, and water quality has deteriorated to more than 2000 ppm of TDS (total dissolved salts) in an area of 100 km^2 (Gururaja Rao et al. 2013).

21.4.1 Causes and Extent of Coastal Land Salinity

Along the coastal tracts of Gujarat, salinity of groundwater broadly varies with geological formations and their disposition with reference to the coast. It is influenced by factors like seawater ingress, inherent salinity of the formations deposited under marine conditions, and structural features. Also, several creeks under tidal influence allow the seawater to invade and deteriorate the groundwater quality in the phreatic aquifers. Thus, the soil and groundwater salinity is a combined effect of (a) inherent formation of water salinity, (b) seawater encroachment due to groundwater overdraft, (c) tidal water incursion through creeks/estuaries, (d) saline water percolation in low-lying marshy lands inundated by seawater, (e) irrigation with saline water, and (f) salt-laden winds/sea sprays. In addition, in such fresh saline aquifers, where freshwater is underlain by saline water at deeper depths, the overdraft of groundwater causes salt water upcoming of the underlying saline water. Along the coast, seawater is creeping underground into freshwater aquifers. It is advancing at an unprecedented rate of half a km a year along the 1600-km-long coastline of Gujarat; thereby salinity ingress covers 550 km^2 new area along the coastline every year (Gururaja Rao et al. 2013). Since the early 1970s, when the salinity ingress was first observed, there are over 2500 villages that are currently affected.

21.5 Sea-level Rise Due to Climate Change

Sea-level rise is a major climate change impact that will have wide-ranging effects on coastal environments (IPCC 2007). Recent projections for 2100 suggest that sea level may be ~0.6–1.5 m higher than the present (Jevrejeva et al. 2010) and ~ 2 m higher under extreme warming scenarios (Grinsted et al. 2009). In view of the large population living along the coastal lines, even small increases in sea level can have significant societal and economic impacts through increased coastal erosion, susceptibility to storm surges, inundation of low-lying areas, saltwater intrusion into groundwater, loss of coastal wetlands, and stresses on ecosystems and community infrastructure.

21.5.1 Lateral Intrusion of Seawater

Lateral seawater intrusion occurs in coastal zones. Though under natural undisturbed conditions, a seaward hydraulic gradient exists in the aquifer with freshwater discharging into the sea, a landward-thinning "saltwater wedge" of heavier saltwater flows from the sea also develops beneath the lighter freshwater. Such lateral seawater intrusion in coastal areas may be enhanced by surface water bodies, as estuaries and rivers, connected to the sea greatly increasing the coastline length if conditions allow seawater to travel inland through these bodies. Pumping from coastal wells can draw salt water downward from such surface sources of saline water. This type of intrusion is usually more local in nature with a potential to contaminate portions of the aquifer near the river. "Salinity ingress has spread its tentacles far and wide on the 1125-km-long Kutchh-Saurashtra coastal belt engulfing 779 villages with a population of 13.3 lakhs making the life of the people miserable." In coastal Gujarat in general and Saurashtra region in particular, high groundwater draft compared to groundwater recharge resulted in lowered groundwater levels. The impacts of the decline in water levels include:

- Drying up of open wells (shallow wells).
- Higher costs for drilling deep tube wells.
- Deterioration of ground quality.
- Drastic change in natural gradient of water in the vicinity of the sea.
- Pumping of water from deep strata has increased the demand of electricity and thus the cost of consumption.

Any salinity mitigation program for coastal regions needs to have the following objectives:

- Arresting salinity ingress from the seawater on to the main land
- Rainwater harvesting in farm ponds and on the other side of the reclamation bund, etc.
- Recharging groundwater to improve the water table and water quality

- Providing lifesaving irrigation for *rabi* season crops
- Arresting/checking siltation and soil erosion
- Increasing the irrigated area through water harvesting structures
- Generation of rural employment
- Improvement of the socioeconomic status of the farming community
- Increasing the community awareness on the possible beneficial effects of the interventions

21.6 Coastal Salinity Issues: Efforts by the High-level Committees

The coastal region of Saurashtra, stretching from Una to Madhavpur, comprises parts of Junagadh district (at present Junagadh and Gir Somnath districts). Increasing pressure of the economic activities along the coast has caused considerable depletion of groundwater, resulting in underground surge of marine water. Looking at the gravity of salinity and its devastating effects, the government of Gujarat formed a High-level Committee 1 (HLC 1) in 1976 for Una-Madhavpur area and a High-level Committee 2 (HLC 2) in 1978 for Una-Bhavnagar and Madhavpur-Malia area for studying the problems of salinity ingress and its management. These Committees, after traversing the problem areas, had suggested diverse measures under four management systems (Table 21.1). The High-level Committee suggested various works of salinity ingress prevention worth ₹640 million (revised cost of ₹1002.4 million) in Una-Madhavpur area, whereas the High-level Committee 2 suggested works of salinity ingress prevention works of ₹1687 million (revised cost of ₹8025.4 million). The High-level Committee 2 further suggested 15 tidal regulators, 40 bandharas, 740 check dams, 25 recharge tanks, 150 recharge wells, 166 km spreading and connecting channels, 2000 nala plugs, and 10,000 ha for reclamation of coastal land at an estimated amount of ₹1860 million.

The Committees also opined that the problem of poor recharge, extensive withdrawal of groundwater, intrusion of tidal waters through creeks/estuaries, and the increase in salinity has to be considered in its totality. No single solution will be

Table 21.1 Measures suggested by HLC 1 and HLC 2 for mitigating salinity ingress in coastal Gujarat

Sr. no.	Various works of salinity ingress under scientific system	
1	Management system	Regulation of lifting underground water and change in cropping system
2	Recharge system	Check dams, recharge dams, recharge wells, recharge reservoirs, and spreading channels
3	Salinity ingress system	Tidal regulators, weirs, freshwater barrier, extraction water barrier, and static barrier
4	Coastal land reclamation	Rejuvenation of salinity land of oceanic areas

applicable to the entire affected area or will be sufficient in isolation. Various measures involving engineering, agriculture, forestry, and social and legal aspects have to form a part of an integrated approach to reduce the water and land salinity problem and improve conditions in the salinity-affected areas. The Committee recommended several salinity prevention techniques, including construction of a large number of structures to achieve the objectives given below:

1. To control surface and subsurface salinity ingression along the coastal stretches
2. To recharge and enhance the quality of underground aquifer of the coastal belt
3. To promote agricultural activities by providing surface water facilities to the farmers in and around the constructed civil structures
4. To achieve an overall improvement in socioeconomic conditions of the village community in the vicinity of the constructed civil structures

Groundwater recharge techniques such as check dams, recharge tanks, spreading channels, and recharge wells as well as afforestation measures were found effective in augmenting the groundwater recharge. Similarly, tidal regulators and *bandharas* were found to be effective in preventing upstream movement of tidal water through river channels. However, the implementation of freshwater barrier was not considered feasible, in view of the large heterogeneity in subsurface arising due to occurrence of cavities in limestone that required substantial quantity of freshwater. Similarly, the extraction barrier that involves continuous pumping and needs elaborate maintenance system was not considered economically feasible due to high initial and recurring costs.

The government of Gujarat had taken up various salinity control and recharge measures recommended by the HLC 1, viz., construction of salinity control structures like tidal regulators and *bandharas* located near the coast and recharge structures like check dams, recharge reservoirs, recharge wells, and recharge tanks located inland on the rivers and local streams, etc. In addition, construction of nala plugs in the upper reaches of the area, afforestation, and spreading channel (Fig. 21.7) works near the coast were also taken up initially by the Gujarat State Land Development Corporation Ltd. and the State Forest Department with finances provided by the Salinity Ingress Prevention Circle. The High-level Committee 1 studied various issues pertaining to the salinity ingress in Bhavnagar-Una reach, Madhavpur-Malia reach, and Malia-Lakhpat reach. The HLC 1 suggested water quality monitoring comprising water table and groundwater salinity during pre- and post-monsoon and to come out with water table and groundwater quality maps.

Based on the High-level Committee's observations and out of the works suggested in the areas of Una-Bhavnagar and Madhavpur-Malia region, construction of 13 tidal regulators, 29 *bandharas*, 15 recharge reservoirs, 661 check dams, 28 recharge tanks, and 4487 nala plugs and afforestation in 5867 ha of land have been completed. Regarding spreading channels, of the suggested 360 km of total length, 141 km has been completed, and the benefits have been accrued. Further, the works suggested by HLC 2 have also been undertaken as per the financial provision made

Fig. 21.7 Salinity prevention works and spreading channel in Coastal Gujarat

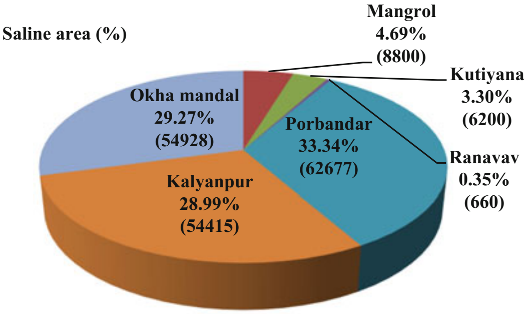

Fig. 21.8 Salt-affected area in (Madhavpur-Okha reach) – values in paranthesis are actual area (ha)

by the 12th Finance Commission, 13th Finance Commission, and National Bank for Agriculture and Rural Development (NABARD) to avail the benefits.

The study further indicated a total of 226.49 MCM withdrawals had taken place against the recharge of 123.94 MCM, with a net over withdrawal/overdraft of 102.55 MCM in 1977. Rainwater harvesting and rainwater conservation further decreased the extent of salinity and enhanced crop production in the region mainly resulting from the decline in irrigation water salinity with concomitant improvement in the quantum of water storage. The report indicated Porbandar followed by Okha mandal (Fig. 21.8) and Kalyanpur had the maximum saline area and Mangrol, Kutiyana, and Ranavav had only marginal area under salinity.

21.7 Coastal Salinity Issues: Efforts by Gujarat Water Resources Development Corporation Ltd. (GWRDC)

The coastal area blocks covered and recommendations of HLCs are briefed below.

Coastal area blocks (1) Bhavnagar-Una reach, (2) Madhavpur-Malia reach, and (3) Malia-Lakhpat reach

Recommendations by HLC Monitoring of groundwater salinity in Madhavpur-Malia reach, Madhavpur-Okha, and Okha-Malia reach and Mangrol taluka of Junagadh district (187 km); Kutiyana, Ranavav, and Porbandar talukas of Porbandar district; and Kalyanpur and Okha mandal talukas of Jamnagar district

21.7.1 Bhavnagar to Una: Monitoring of Groundwater Conditions

The area comprises the coastal belt of Bhavnagar, Ghogha, Talaja, and Mahuva talukas of Bhavnagar district, Rajula and Jafrabad talukas of Amreli district, and Una taluka of Junagadh district of Gujarat state. The monitoring was done by GWRDC (435 open wells and 67 geo-electrical sounding profiles). Artificial recharge to check runoff and increasing groundwater recharge was undertaken (Fig. 21.9). Certain areas in Talaja, Una, and Mahuva are prone for seawater ingress. The extent of saline area is given in Table 21.2.

Reports by the High-level Committee 2 that studied the seawater ingress in Bhavnagar-Una reach with 183 km spread consisting of the coastal belt of Bhavnagar, Ghogha, Talaja, and Mahuva talukas of Bhavnagar district, Rajula and Jafrabad talukas of Amreli district, and Una taluka of Junagadh district of Gujarat state indicated that during 2011, the utilizable recharge, balance, and effective draft

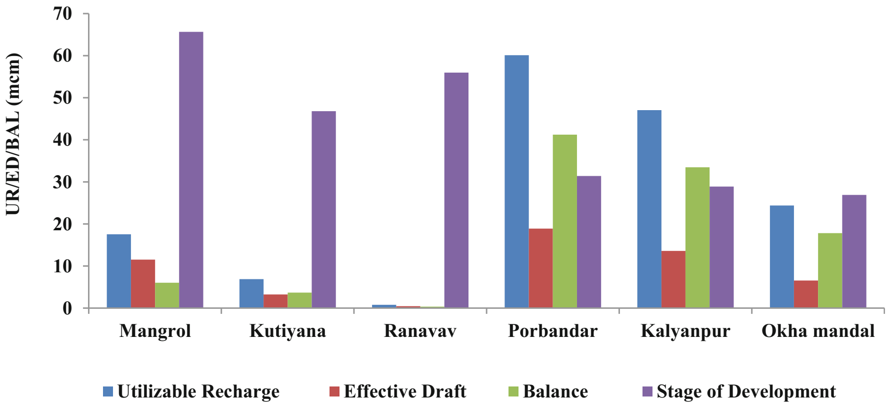

Fig. 21.9 Groundwater estimations in Madhavpur-Okha reach – 2011 (Source: GWRDC Report)

Table 21.2 Salt-affected area in HLC 1 (Una-Madhavpur reach) during 1988–2015 and 2014–2015

Taluka	Area improved, ha May 2015	Area deteriorated, ha May 2015	Net area (ha) improved/ deteriorated May 2015	Affected area, May 1988	Affected area, May 1988–2015
Mangrol	2025	1589	436	19,707	19,271
Malia (H)	995.31	730	266	4937	4671
Veraval	12,284.38	61	12,223	30,693	18,470
Kodinar	2226.56	33	2194	16,126	13,932
Una	6492.19	9	6483	24,751	18,268
Total	24,023.44	2421.88	21,602	96,214	74,612
Marshy land				13,757	13,757
Total				**109,971**	**88,369**

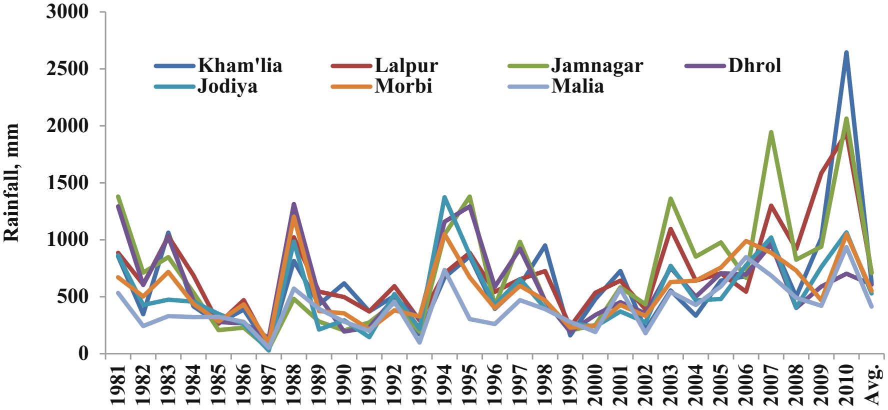

Fig. 21.10 Rainfall in Okha-Malia reach during 1981–2010

estimated were better in Porbandar, Kalyanpur, and Okha mandal when compared to Mangrol and Kutiyana.

21.7.2 Rainfall

Rainfall data in Okha-Malia reach during 1981–2010 (Fig. 21.10) indicated that higher rainfall facilitated the groundwater recharge with concomitant decrease in salinity. Recharge due to precipitation is significantly higher when compared to the control measures (Fig. 21.11). The control measures, however, further boosted the groundwater status in the region during 1990–2015 with conspicuous improvement noticed during the latter part of the study period, i.e., 2002–2015.

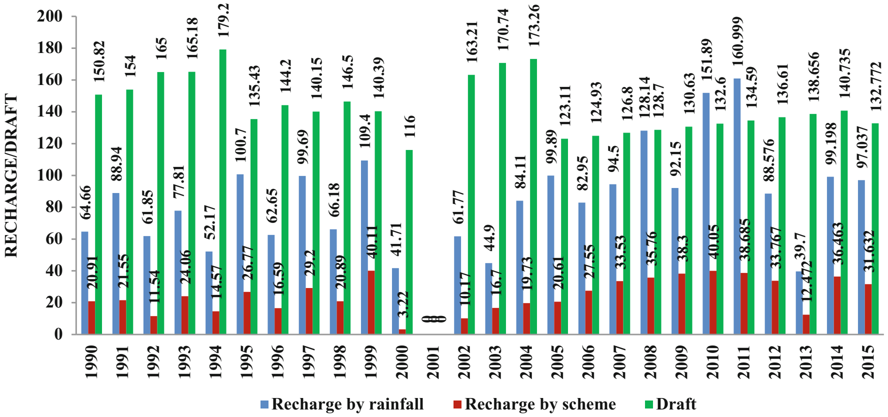

Fig. 21.11 Recharge from rain harvesting schemes and draft in HLC 1 area during May 2015

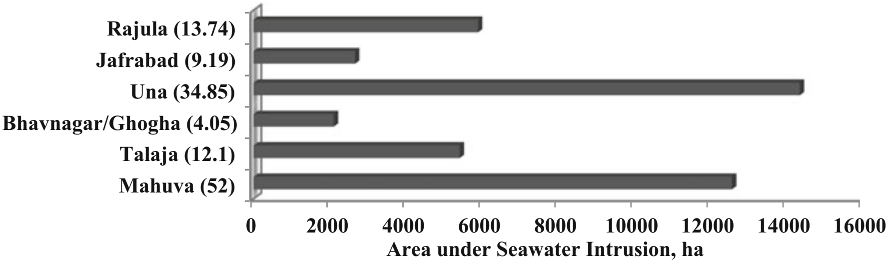

Fig. 21.12 Area affected by Seawater Intrusion (ha) in Bhavnagar-Una reach (figures in parantheses are intrusion in km – cumulative)

Studies also indicated the maximum seawater intrusion to a tune of 34.85 km amounting to 15,000 ha in Una and 52 km to a tune of 12,800 km in Mahuva with the least being observed in Jafrabad and Bhavnagar-Ghogha area (Fig. 21.12).

The HLC 1 (1976) and HLC 2 (1978) for Una-Madhavpur studied the measures taken for controlling the seawater intrusion in the coastal Saurashtra along the 765-km-long stretch comprising Una-Bhavnagar and Madhavpur-Malia reaches. The salinity ingress mitigation measures had a profound influence on the benefited area, which has been brought under agriculture and allied activities (Table 21.3).

21.7.3 Effect of Control Measures: Case studies

Una-Madhavpur

The extent of salinity ingress in Una-Madhavpur during 1977–2015 is depicted in Fig. 21.13. The data indicated a gradual decline in the distance of seawater ingress across all talukas suggesting the efficacy of the control measures. The extent of salt-affected area in this region also showed simultaneous declining trend (Fig. 21.14).

Table 21.3 Work done on salinity ingress prevention by SIPC (Rajkot) in coastal Gujarat

Intervention	Execution done	Expenditure, Rs. in lakhs	Total cost	Storage, MCM	Total	Benefited area, ha	Total
Tidal regulator	HLC 1	4983.82	10,879.28	31.24	178.58	5531.00	19,970
	HLC 2	5895.46		147.34		14,439.00	
Bandharas	HLC 1	2082.25	6982.71	29.50		4065.00	17683
	HLC 2	4900.46		42.26	71.76	13,618.00	
Recharge reservoirs	HLC 1	945.07	2936.55	13.38	45.96	3430.00	7770.00
	HLC 2	1991.48		32.58		4340.00	
Recharge tanks	HLC 1	2.74	971.64	0.31	2.82	140.00	3459.00
	HLC 2	968.00		2.51		3319.00	
Spreading channel	HLC 1	1692.09	10,291.62	0.79	2.54	10,168.00	29,997.00 [220.07 km]
	HLC 2	8559.93		1.75		19,829.00	
Check dam		3133.38		24.42		8674.00	8674 [672 os]
Percolation tank		209.83		1.64		630.00	
Erosion control		1203.96		–		35.25	

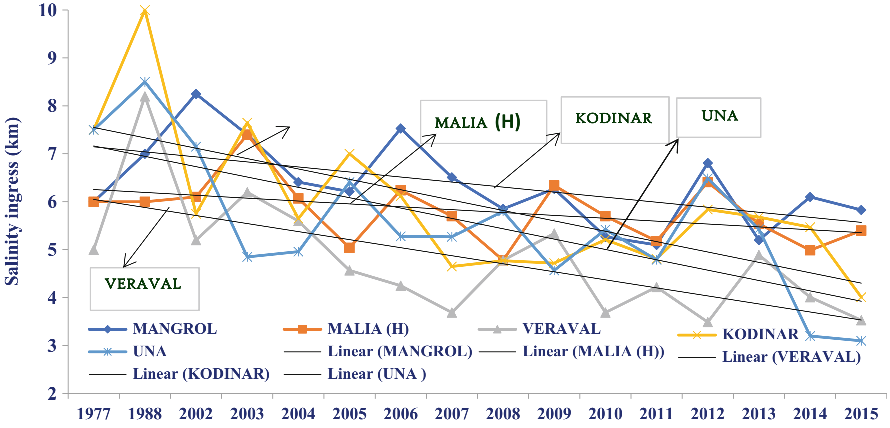

Fig. 21.13 Extent of salinity ingress (km) in different talukas in Una – Madhavpur Reach during 1977–2015

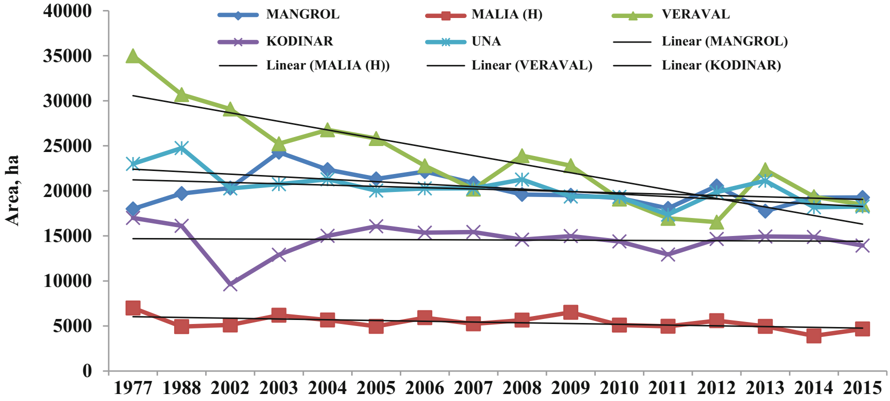

Fig. 21.14 Extent of salt-affected soils (ha) in different talukas in Una – Madhavpur Reach during 1977–2015

Rajkot Circle

Salinity Ingress Prevention Circle (SIPC), Rajkot, also carried out work on salinity ingress control measures with an aim at conserving rainwater, groundwater quality improvement, and prevention of surface and groundwater salinity due to spreading of tidal water. The advancement of saline tidal water has been prevented by the tidal regulators and weirs. Moreover, the damages to the fertile agricultural lands have also been considerably minimized with concomitant reduction in groundwater salinity. The efforts led to betterment of 74,512 ha land due to the storage of 318.04 MCM of freshwater and improved groundwater quality with concomitant rise in water table almost to an extent of 2.50 m in the region primarily from

Table 21.4 Remedial measures adopted in the Kutch region of Gujarat

Sr. no.	Particulars	Completed	Storage capacity (Mm3)	Benefited area (ha)	Expenditure (Rs. in million)
1	Medium irrigation schemes	20	281.74	21292	NA*
2	Minor irrigation schemes (Panchayat)	2170	298.45	298.45	NA*
3	Bandharas	53	90.51	35,710	2120
4	Big river check dam (cost Rs. > 25 lakh)	343	88.90	26,612	1660
5	Small check dam (cost Rs. < 25 lakh)	521	13.26	7345	540
6	With public participation (under 80:20 and 60:40)	5937	116.12	38,845	2140
7	Tanks and safe stages' works	1697	144.20	30,529	660
8	Radial channel work	3	4.71	930	30
9	Recharge wells 805	805	0	0	50
10	Recharge tanks	3	0.09	100	10
11	Deepening of tanks	82	1.38	590	70
	Total	9634	1039.36	196,470	7280

groundwater recharging, and salinity mitigation/control measures also benefited about 2.6 lakh hectares of land from getting saline. In addition, salinity ingress control measures also helped in the decline in groundwater salinity and improvement in crop yields as well as socioeconomic conditions of people and the overall prosperity of the region.

Kutch Region

The coastal strip between Malia and Lakhpat with 360 km stretch having geographical area of 3712 km^2 comprising of 245 villages of 7 talukas in Kutch district have been affected by salinity. Based on the suggestions by the High-level Committee 2, the remedial measures and the consequent benefits accrued are given in Table 21.4.

21.8 Impact of Salinity Mitigation Measures on Agriculture

The salinity ingress has major impact on the agriculture sector. Increase in level of salinity in water and soil has resulted in changing the cropping pattern drastically. The area under horticulture is reducing gradually, and no new plantation of mango and coconut is carried out by the farmers. The farmers having mango orchards are facing major challenge to their plantation since irrigating mango orchard using saline water affects the production in terms of quality as well as quantity. The cropped area of pulses has reduced in coastal areas. Groundnut, one of the major crops, is replaced by cotton which is known for its salt tolerance capacity. Increase in crop yields mainly results from improved groundwater table, water quality, and use of the freshwater harvested in water storage devices for providing irrigation at strategic times of crop growth. Paddy yield increased by 60% followed by sugarcane (33%), while *kharif* and *rabi* pulses showed 41 and 37% increase, respectively. Likewise, both rabi and summer vegetables showed about 35–40% increase indicating the overall agricultural improvement resulting from the interventions. From the interventions, it is evident that water being an important constraint, its conservation and judicious use have become a clear possibility in the coastal Gujarat which resulted in increased cultivated area and household income and improved employment generation. Salinity control measures in different coastal districts of Gujarat had helped the farmers to go for cash crops like Bt cotton, castor, groundnut, and onion, along with wheat and millets. Improvement of groundwater status and prolonged availability of conserved water in check dams resulted in yields of groundnut, cotton, and wheat to a tune of 66, 34, and 33%, respectively. In certain parts of Amreli district (Sikarwar and Gururaja Rao 2014), where some of the farmers, who were not taking crops like cotton and onion for want of water, had successfully grown both cotton and onion with a production of 20 and 80 quintals per ha, respectively. Changes brought about by the interventions in different coastal districts are depicted in Fig. 21.15.

21.9 Coastal Salinity Issues: Agro-interventions Using Salt-tolerant Crops

In order to understand farmers' response and strategies to cope with changes in the environment and to analyze the interface between changes in the natural resource base and in the socioeconomic environment, studies were conducted by giving primacy to interventions developed, i.e., cultivation of food and high-value crops like wheat and cotton, in different farm units in the coastal areas of Gujarat. Cultivation of salt-tolerant cotton and wheat varieties is an ecologically and economically viable option to overcome the salinity stress. Efforts were made by CSSRI and Regional Research Station Bharuch along with Coastal Salinity Prevention Cell (CSPC) to study the prospects and impacts of salt-tolerant herbaceum (desi) cotton genotypes and wheat varieties in southern, central, and Saurashtra regions of coastal Gujarat. It was observed that desi cotton was more suitable and profitable to farmers in rainfed coastal saline conditions. Desi cotton accessions "G. Cot. 23" gave cotton seed yield ranging from 1.6 to 1.9 Mg ha^{-1} under the average soil salinity of 7.6 dS m^{-1} where traditional varieties like Gheti and Dhummad gave seed cotton yield in the range of 1.3–1.4 Mg ha^{-1} (Gururaja Rao et al. 2014b). In saline areas with soil EC ranging from 5.9 to 7.2 dS m^{-1}, salt-tolerant wheat varieties "KRL 210" and "KRL 19" yielded in the range of 3.60–3.95 Mg ha^{-1} where normal traditional varieties yielded less than 2.5 Mg ha^{-1} (Gururaja Rao et al. 2016).

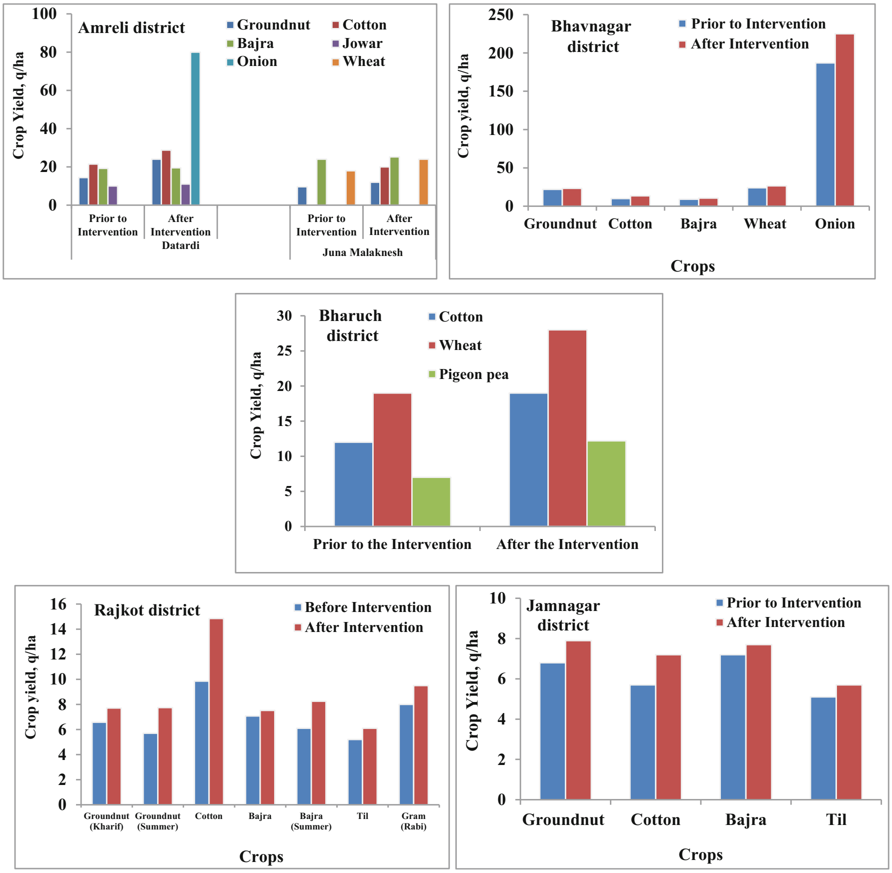

Fig. 21.15 Impact of salinity mitigation measures on crop yields in different coastal districts during pre- and post-implementation phases

Cultivation of salt-tolerant herbaceum cotton (G. Cot. 23) in coastal areas of Bharuch, Anand, Ahmedabad, and Junagadh districts indicated significantly higher cotton yield in Bara tract (VIKAS and ATAPI) compared to Saurashtra (VRTI) in the years 2012 and 2013 (Table 21.5). This is mainly because of the cultivar being less prone to diseases, which had become a center point for their further adoption. The input costs in desi cotton were much less (30–35% less) when compared to hybrids or Bt lines mainly due to low cost of seed, lesser pesticide use, and reduced irrigation, and also their response to saline water irrigation in the desi cotton lines has gained momentum in the region.

Saline lands having soil salinity of 8–10 dS m^{-1} had been profitably brought under cultivation with herbaceum cotton, “G. Cot. 23” in all the three coastal regions of the state. This had resulted in gross income in the range of ₹70,000–₹75,000 ha^{-1} and net income of ₹45,000–₹50,000 ha^{-1}, particularly in South Gujarat, i.e., in Bojadra and Kalak with B:C ratio of 1.8–2.0. The lower salt tolerance coupled with

Table 21.5 Seed cotton yield in South Gujarat and Saurashtra during 2011–2013

NGO	Cotton seed yield (Mg ha^{-1})		
	2011	2012	2013
VIKAS	1.68	1.72	1.84
ATAPI	1.62	1.74	1.79
MAHITI	1.61	1.76	1.81
VRTI	1.56	1.59	1.68
SEm±	0.024	0.038	0.035
CD0.05%	0.053	0.062	0.058

Source: Gururaja Rao et al. (2016)

Table 21.6 Wheat yield in different clusters in coastal Gujarat taken up by NGOs

NGO	Soil ECe (dS m^{-1})	Average wheat yield (Mg ha^{-1})[a]	
		KRL 19	KRL 210
SSKK	6.02–6.9 (6.49)	3.72	3.64
MAHITI	5.90–6.82 (6.38)	3.92	3.83
VIKAS	6.16–6.74 (6.39)	3.85	3.82
ATAPI	5.88–6.32 (6.09)	3.97	3.96
TCSRD	6.34–6.63 (6.42)	3.71	3.57
GHCL	6.16–6.87 (6.46)	3.61	3.63
SEm±		0.047	0.045
CD (5%)		NS	NS

[a] Average of 4 field units of 1.0–1.5 ha at each site

less seed cotton yields of hybrids and Bt lines compared to herbaceum and arboreum (Gururaja Rao et al. 2013, 2016) formed a basis for the farmers going for desi cottons in coastal saline areas. Further, earlier studies by Gururaja Rao et al. (2013, 2016) also indicated lower input costs primarily due to reduced disease incidence in desi cotton coupled with reduced number of irrigations.

Farmers' field trials undertaken by CSSRI, Bharuch, through the NGOs like SSKK and GHCL (Saurashtra), MAHITI (Bhal area), VIKAS and ATAPI (Bara tract), and TCSRD (Jamnagar district) with salt-tolerant wheat indicated almost consistent seed yields (3.6–3.95 Mg ha^{-1}) of "KRL 210" and "KRL 19" under soil salinity of 5.9–7.2 dS m^{-1}. Similarly, field trials conducted at Una, Veraval, and Jafrabad talukas (coastal areas of Junagadh district) indicated that seed yield of "KRL 210" ranged from 3.4 to 3.95 Mg ha^{-1} across all the sites. Una and Veraval showed seed yield of about 3.8 Mg ha^{-1} at salinity ranging from 6.4 to 6.9 dS m^{-1}, whereas at similar salinity, the seed yields reduced by 20 kg ha^{-1} at Jafrabad due to high clay content of the soil, since even low salinity become detrimental for crop production under clayey type of soils. However, the seed yield of the salt-tolerant wheat lines was much higher than local variety "Lok 1" which yielded about 2.5–3.0 Mg ha^{-1} indicating the superiority of these lines to saline conditions and their better suitability for saline areas of coastal Gujarat (Table 21.6; Gururaja Rao et al.

2016). The cultivation of salt-tolerant varieties (Gururaja Rao 2004; Gururaja Rao et al. 2016), thus, is an effective biological approach by the farming community to manage coastal saline lands in Gujarat. Cultivation of salt-tolerant varieties of crops in salt-affected areas is thus considered as the very prudent option with less environmental degradation.

21.10 Way Forward

Salinity of soils and irrigation water is an inherent and consistent problem in the coastal regions in general and Gujarat in particular; concerted efforts need to be made to make agriculture as the viable option. The efforts should be made for providing adequate irrigation water and remunerative alternate crops suited to the prevailing conditions. To achieve this, the prime efforts are to arrest salinity ingress: conservation of rainwater, groundwater recharging, and educating the farmers in judicious use of the resources. The efforts made by the state government as per the recommendations of the HLCs, Salinity Ingress Prevention Circle, GSLDC, and other NGOs like CSPC and research institutions like CSSRI, though proved beneficial, these organizations need to be brought on a common platform to deduce workable models along with the end users, “the farmers” for bringing prosperity to the region. Efforts are also needed:

- To motivate the villagers and farmers to involve in the works with full commitment to take care of the interventions to derive the maximum benefits.
- Maintenance of the structures and also possible repairs need to be entrusted to the beneficiaries or corresponding local bodies with provision of adequate funding.
- Introduction of new, high-yielding and salt-tolerant crops, e.g., fodder bean in Saurashtra.
- As salinity is the key issue that affects the well-being of people living in the area, the livestock, and the crops, program of this nature should have an association with institutions dealing with such issues to derive benefits timely.
- Since transfer of technology to the end users is an important aspect, time-to-time on-site/off-site training programs, farming models, village-level meetings, presentations/demonstrations, or effective communication means need to be taken up which would act as motivation to the farmers/villagers.

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Agro-interventions for Sustainable Management of Salt-affected Vertisols in India

22

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Abstract

Salinity and sodicity of soils and irrigation waters are major environmental problems in the arid and semiarid regions of the world. While these problems are natural in their genesis in the coastal regions, they occur primarily due to anthropogenic activities in the irrigation command areas resulting from faulty irrigation. It is the product of complex interaction of many variables, which reduce the current and the potential capability of soils to produce goods and services. In India, reports have indicated an occurrence of 6.73 million ha of salt-affected soils. Vast areas are in imminent danger of turning barren, and production and productivity have simply declined due to secondary salinization. Soil salinity problems are further compounded where the groundwater is highly saline, and such areas *by and large* remain barren for want of economically viable agro-interventions, thereby affecting the livelihood of the farmers, while both saline and sodic Vertisols can be brought under production system through diverse

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agro-interventions. Research conducted on saline Vertisols resulted in viable technologies for cultivating field crops like cotton and wheat, forages including halophytic grasses, economic halophytes like *Salvadora persica*, seed spices like dill, medicinal and aromatic plants, agroforestry with forest and fruit species, biofuel species like *Jatropha curcas* and ideal farming system models for resource-poor farmers. For sodic soils, rice and wheat systems were given priority under amendment application. These interventions along with their impacts are discussed in this chapter.

Keywords
Agro-interventions · Saline vertisols · Sodic vertisols · Halophytes · Forages · Farming system model

22.1 Introduction

Global demand for food, fibre and bioenergy is growing at rapid rate. However, the growth rate in agriculture in most of the developing countries has failed to meet the needs of burgeoning population. Land and water degradation resulting from anthropogenic activities is considered as the principal constraint in achieving the desired agricultural growth rate in food grain production. Soil salinization is considered as an important factor contributing to human-induced land degradation (Zhu 2001). Abiotic stresses, viz. drought and salinity, while lowering the crop quality and yields, also restrict the geographical range over which crop production becomes viable (Thakur et al. 2010). Soil salinity has been a major concern to global agriculture throughout human history (Lobell et al. 2007). About 6.73 million hectares (Mha) of land is affected by salinity and sodicity in India (Singh et al. 2010; Mandal et al. 2010). Salinity development in India charts a parallel path with irrigation development. The advent of new irrigation projects with inadequate attention at the planning stage coupled with unscientific irrigation has aggravated the problem.

The black cotton soils also known as Vertisols are heavy clayey soils rich in montmorillonite clay minerals with nodular lime in the subsoil (Szabolcs 1989). These soils swell on wetting and crack on drying (Fig. 22.1) and show very-poor infiltration rates when wetted, thereby limiting the leaching of salts. These are deep, dark-coloured clayey soils of predominantly smectitic mineralogy with a high proportion of swelling clays, i.e. montmorillonite-rich clays (Ahmad 1983), which in dry state develop typical cracks of at least 1 cm wide and reach a depth of 50 cm or more. As a result of wetting and drying, expansion and contraction of the clay minerals take place. The slippage of one soil block over the other leads to the formation “slickensides”. Expansion and contraction also cause the formation of microtopographic features known as “gilgai”, a distinctive microrelief. These soils have characteristic cyclic pedons, which make them different from other soils. Vertisols are not a uniform soil entity, and as they occur under very different agroclimatic environments, transfer of technology thus becomes a limitation in

Fig. 22.1 Typical Vertisols with distinct cracks

their management. The development of salinity and sodicity in black soil region is generally associated with poor drainage and waterlogging.

22.2 Pedo-climatic Environment

The pedo-climatic environment supporting these soils varies from semiarid to subhumid tropics in India. Such climates are characterized by hot and dry pre-monsoon summer months (March to May) followed by well-expressed summer monsoon months (June to September). Vertisols occur principally in the hot environments with marked alternating wet and dry seasons. The mean annual rainfall ranges from 500 to 1500 mm of which 80–90% is received during monsoon months. The soil moisture control system remains dry either completely or in part for 4–8 months in a year suggesting an ustic moisture regime.

22.3 Distribution of Vertisols

Vertisols and associated soils are the most widely distributed soils in the world that can be found under varied climatic conditions that spread over five continents mainly in tropical and subtropical areas and located mostly in Asia and Africa (Dudal and Bramao 1965). Worldwide, these soils cover 257 Mha of which about 76.4 Mha occurs in India (Table 22.1, Murthy et al. 1982). Vertisols and associated soils are found to occur in nearly four agroclimatic conditions of India, i.e. arid, semiarid, dry subhumid and moist subhumid conditions (Fig. 22.2). The largest Vertisol areas are on sediments that have a high content of smectitic clays or produce such clays upon post-depositional weathering (Sudan) and on extensive basalt plateaus (India). Vertisols and associated soils are predominant in Maharashtra (29.9 Mha), Madhya Pradesh (16.7 Mha), Gujarat (8.2 Mha), Andhra Pradesh (7.2 Mha), Karnataka (6.9 Mha), Rajasthan (2.3 Mha) and Tamil Nadu (3.2 Mha). Of these, salt-affected

Table 22.1 Distribution of black cotton soils (Vertisols) in India

S. no.	State	Area (Mha)	Per cent of total black soil area of the country	Per cent of total geographical area of country
1	Maharashtra	29.9	39.1	9.1
2	Madhya Pradesh	16.7	22.0	5.0
3	Gujarat	8.2	10.7	2.5
4	Andhra Pradesh	7.2	9.4	2.2
5	Karnataka	6.9	9.0	2.1
6	Tamil Nadu	3.2	4.2	1.0
7	Rajasthan	2.3	3.0	0.7
8	Orissa	1.3	1.7	0.4
9	Bihar	0.7	0.9	0.2
Total		76.4	100.0	23.2

Source: Murthy et al. (1982)

Vertisols measure 0.54 Mha in Maharashtra, 0.12 Mha in Gujarat state and 0.034 Mha in Madhya Pradesh (Chinchmalatpure et al. 2011).

22.4 Characteristics of Vertisols

22.4.1 Morphological Characteristics

The morphological characteristics comprise expression, shape and orientation of the structural aggregates and depth and width of cracks developing on drying. The structural arrangement together with the wide cracks is probably the most striking morphological feature of Vertisols. In most cases, the surface horizons exhibit large and well-developed angular blocky or prismatic structures, while in the subsoil wedge-shaped structural elements of all sizes do occur. A typical profile of Vertisols has A-(B)-C-horizons; the A-horizon comprises both the surface mulch (or crust) and the underlying structured horizon that changes gradually with depth. Important morphological characteristics such as soil colour, texture, element composition, etc. remain uniform throughout the solum. A calcic horizon or a concentration of soft powdery lime may be present in or below the vertic horizon. Vertisols differ in surface characteristics as compared to other soils, and these strongly influence their reaction to soil tillage operations. There are following two broad groups of these soils:

22.4.1.1 Self-mulching Vertisols

These soils have a fine (granular or crumb) surface soil of 2–30 cm thickness with a fine tilth produced by desiccation and soil shrinkage during dry season. When

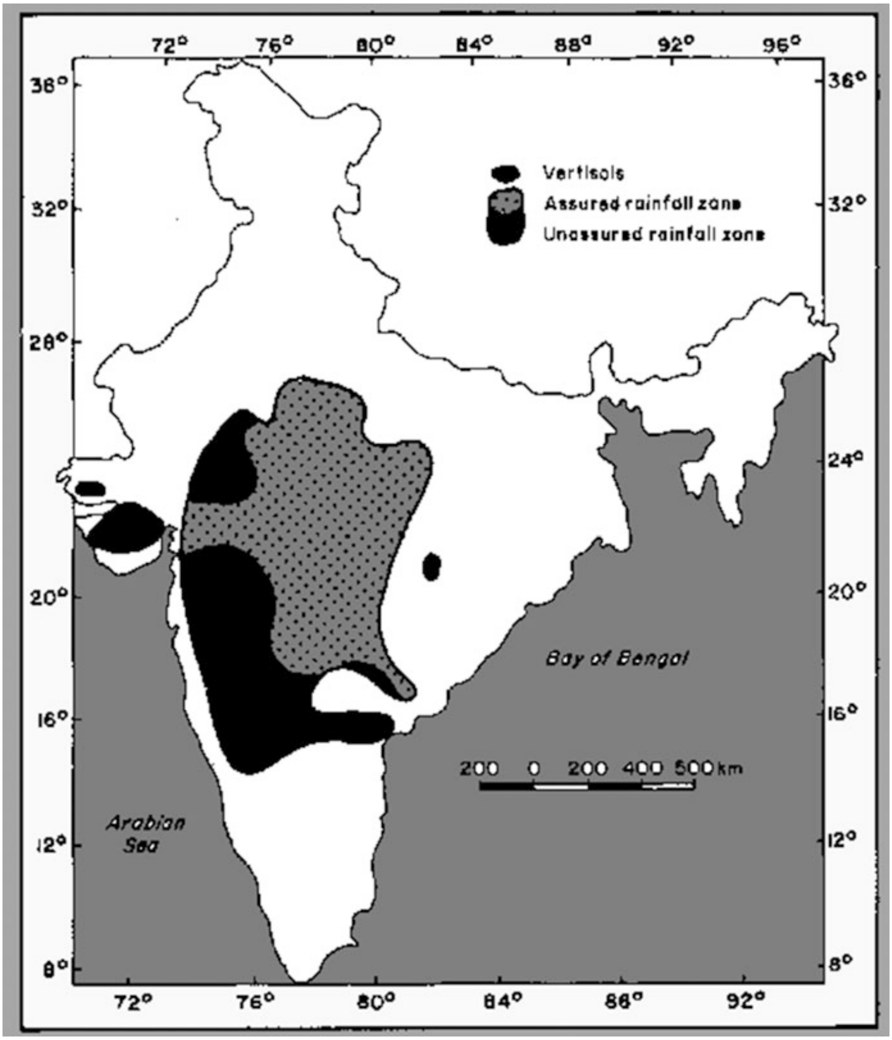


Fig. 22.2 Distribution of Vertisols in India

ploughed, the clods in these soils disintegrate when subjected to repeated wetting and drying. Such soils require mechanical tillage if they are to be cultivated.

22.4.1.2 Crusty Vertisols

These soils have a thin, hard crust in the dry season. When ploughed, they produce large and hard clods which may persist for 2–3 years before they crumbled enough to permit the preparation of a good seedbed. The self-mulching versus crusting characteristic is related to the tensile stress of the soil, mainly influenced by the soil texture. These soils are also strongly self-mulching when they contain appreciable amounts of fine, sand-sized calcareous concretions; and these apparently disturb the continuity of the clayey soil material. Other observations have shown that under higher rainfall, Vertisols do not generally contain calcareous concretions. Very high amounts of sodium result in the formation of a hard surface crust.

22.4.2 Physical Characteristics

The dry Vertisols have a very hard consistence, and wet Vertisols are (very) plastic and sticky. It is generally true that Vertisols are friable only over a narrow moisture range but their physical properties are greatly influenced by soluble salts and/or adsorbed sodium. The most important physical characteristics of Vertisols are low hydraulic conductivity, low infiltration rates, bulk density and salt content. The clay content generally varies from 40% to 95% with narrow difference within the profile. Infiltration of water is initially rapid in dry Vertisols with surface mulch or fine tilth. However, once the surface soil is thoroughly wetted and cracks closed, the rate of water infiltration becomes almost nil. If, at this stage, the rains continue (or irrigation is prolonged), Vertisols flood readily. Vertisols, *by and large*, are soils with good water-holding properties. However, a large proportion the water held between the basic crystal units is not available to plants. When these soils are irrigated, the high seepage leads to a shallow water table conditions causing secondary salinization or sodiumization. The structural stability of Vertisols remains low which makes them very susceptible to water erosion.

22.4.3 Chemical Characteristics

Majority of Vertisols have a high cation exchange capacity (CEC) and a high base saturation percentage (BS). Dominant cations are Ca^{2+} and Mg^{2+} while Na^{+} plays an important role. The pH values are in the range of 6.0–8.0. Higher pH values (8.0–9.5) are seen in Vertisols with high exchangeable sodium percentage (ESP). A typical profile is depicted in Table 22.2. Salinity in Vertisols may be inherited from the parent materials or may be caused by over-irrigation. In coastal regions, Vertisols with high soluble salts and/or with low sulphates are seen. Leaching of excess salts is hardly possible. It is possible to flush salts that have precipitated on the wall of cracks. Surface leaching of salts from the paddy fields in India was achieved by evacuating the standing water at regular intervals.

22.5 Production Constraints

Vertisols, because of their hard consistence when dry and very plastic and sticky when wet, are difficult to work. Their workability is often limited to very short periods of medium (optimal) water status. Tillage operations, however, can be performed in the dry season with heavy machinery. Mechanical tillage in the wet

Table 22.2 Physical-chemical characteristics of the typical Vertisol (Shajapur, Madhya Pradesh)

Depth	EC_e			Ionic composition (meq l^{-1})						Particle size (%)			$CaCO_3$	CEC
cm	dS m^{-1}	pH_s	ESP	Ca^{2+}	Mg^{2+}	Na^+	CO_3^{2-}	HCO_3^-	Cl^-	Sand	Silt	Clay	%	meq 100 g^{-1}
0–13	3.5	8.3	60	5.1	5.1	26	Nil	6.3	23.0	15.5	50.0	34.5	8.0	12.0
13–31	1.7	8.4	65	4.2	1.0	8	Nil	9.2	9.0	30.0	45.5	29.5	7.0	12.8
31–62	2.8	8.2	73	2.1	4.8	14	Nil	14.2	8.8	3.0	56.0	42.0	12.8	27.0
62–94	1.6	9.4	51	2.2	4.9	8	Nil	10.2	8.1	4.0	52.5	43.5	21.2	19.0
94–126	6.5	9.1	51	6.1	8.8	59	Nil	87.0	21.0	7.0	46.0	47.4	21.4	25.0
126–158	2.5	8.7	56	2.9	5.1	18	Nil	8.8	10.8	3.0	54.0	48.0	18.7	17.7

Source: Bhargava (1989)

season causes serious soil compaction; hence wet lands are really impassable. Vertisols are poorly drained, and thus leaching of soluble salts is also limited. This is due to very low hydraulic conductivity, i.e. once the soil has reached its field capacity, practically no water movement occurs. Flooding can be a major problem in areas with higher rainfall. Surface water may be drained by open drains. Mole drainage is virtually impossible.

The adverse physical properties and poor workability of Vertisols are major obstacles to agricultural land use, especially in low-technology societies. These soils have a considerable potential for agricultural production, but special management practices (tillage and water management) are required to secure sustained production. Though these soils have great potential for productive cropping as the stored subsoil water can sustain crops through drought/stress periods, the current level of crop production in harsh environments, viz. saline and waterlogging conditions, is very low. Saline and sodic Vertisols may develop under irrigation, but they are rare under natural conditions (Chinchmalatpure and Gururaja Rao 2009). Thus, the increasing problem of salinity of soils and groundwater in the Vertisol region in India is of great concern that needs a holistic approach for their management.

Vertisols are base-rich soils and are capable of sustaining continuous cropping. Normally, nitrogen and phosphorus are deficient. Phosphate fixation (as tricalcium phosphate) may occur but is not a major problem. Potassium contents are variable. Secondary elements and micronutrients are often deficient. In semiarid areas free carbonate and gypsum accumulations are common. The production constraints that prevail in Vertisols include:

- Much reduced permeability in swollen state so that both infiltration and internal drainage are very low
- Poor aeration of wet soils and related root development
- Narrow optimum moisture range for tillage and seeding operations
- Germination poor and difficulties associated with rapid drying of granular surfaces and scaling and crusting
- Salinity hazards associated with rising groundwater table and use of poor-quality irrigation water
- Salinity developed due to irrigation under canal command areas

22.6 Salinity/Sodicity Problems in Vertisols

22.6.1 Relation Between Salinity and Sodicity

The effect of electrolyte concentration and SAR and/or ESP on flocculation and hydraulic conductivity (Ks) indicated that the ESP of both the saline and sodic soils increased with electrolyte concentration, and SAR studied by Nayak et al. (2006)

and Chinchmalatpure et al. (2014) indicated that the critical coagulation concentration increases with increase in the ESP of soil. An electrolyte concentration of 20 meq l^{-1} is needed to cause flocculation of clayey soil at ESP of 6 and silty clayey soil at ESP of 10, beyond which, these soils undergo structural degradation. Their studies also indicated that at salinity of ≤ 2 dS m^{-1}, the Vertisols can be grouped as sodic when the ESP is > 6 and > 10 in clayey and silty clayey soils, respectively. Similarly, at salinity of 2–4 dS m^{-1}, the Vertisol can be grouped as sodic when the ESP is > 13 and > 21 in clayey and silty clayey soils, respectively. At higher salinity, i.e. > 6 dS m^{-1}, even at fairly high ESP also, the soil Ks and dispersion are not affected adversely. It can be fairly concluded that the coupled salinity and ESP values be considered as the limit for sodicity classification.

22.6.2 Saline Vertisols

Saline soils contain excess neutral soluble salts like chlorides and sulphate of sodium, calcium and magnesium with $EC_e > 4$ dS m^{-1}, $pH < 8.2$ and $ESP < 15$. Saline black soils due to their inherent physico-chemical constraints such as high clay content, low hydraulic conductivity and narrow workable moisture range are very difficult to work with. Osmotic effect of salt; toxic concentration of soluble ions like Na, Cl and B; and reduced availability of essential nutrients due to competitive uptake affect plant growth in this type of soil. Excess salinity in these black soils results in delayed germination, poor crop stand, stunted growth and lowered crop yields.

22.6.3 Sodic Vertisols

Sodic soils are characterized by high exchangeable sodium percentage (ESP), electrical conductivity (EC_e) < 4 dS m^{-1}, pH > 8.2 and presence of higher amount of carbonate and bicarbonates of sodium. Some sodic soils are also termed as saline sodic as they contain large quantity of soluble salts and EC_e is > 4 dS m^{-1}. In sodic soils, sodium is the dominant cation on the exchange complex which disperses with clay and imparts adverse soil physical conditions, viz. low permeability, crusting and hardening of the surface soils upon drying. Dense, slowly permeable sodic subsoils lower the supplies of water, oxygen and nutrients requisite to obtain optimum yield (Rengasamy and Olsson 1991). Besides, high Na content results in poor crop growth and yields.

22.6.4 Distribution and Characteristics of Salt-affected Vertisols

The statewise distribution of salt-affected soils in India (NRSA and Associates 1996) shows that out of total 76.4 Mha black cotton soil area (Table 22.1), about 1.77 Mha area of sodic soils falls in black soil region. The Vertisols of Bhal area and Bara tract

Fig. 22.3 Highly degraded saline Vertisol in Bara tract of Gujarat

in Gujarat (Fig. 22.3) are generally very deep (150–200 cm), fine textured with clay content ranging from 45% to 68%. These soils are calcareous in nature with calcium carbonate (2–12% $CaCO_3$) occurring in the form of nodules, *kankar* and powdery form and exhibit alkaline reaction. While the soils of Bhal area are highly saline, the soils of Bara tract have significant concentration of soluble salts in subsoils, although the concentration in surface layer is low. In Bara tract, it was found that only 39.6% of surface soils are free from salinity (< 2 dS m^{-1}), 49.3% soils are saline (2–4 dS m^{-1}) and only 11.1% soils have salinity greater than 4.0 dS m^{-1}, whereas 10% of the subsoil are having salinity less than 2 dS m^{-1}, 15% between 2 and 4 dS m^{-1} and 75% greater than 4 dS m^{-1} (Gururaja Rao et al. 2001c, 2013d).

Sodic Vertisols are characterized by high pH (> 8.2), high exchangeable sodium, high $CaCO_3$, very low organic matter content and poor physical conditions. The critical values of ESP depend on the electrolyte concentration of soil solution and range from 5 to 15 (Shainberg 1984). Loveday and Pyle (1973) working on a range of soil types of Australia reported that the differences in critical ESP are due to the differences in EC of the soil solution and the surface soils found to disperse when ESP reaches the critical value of 8 and more, whereas Northcote and Skene (1972) reported that the soils begin to disperse when ESP reaches over 6. Drainage in these soils gets completely impaired due to higher dispersion of clay even at an ESP of 5 (Kadu et al. 1993). Robinson (1971) working on Vertisols of Sudan reported highest cotton yields under ESP of 8–16. The hydraulic conductivity of the sodic soils is affected by the initial swelling followed by clay dispersion (Gupta and Verma 1984). Swelling reduces the pore size and dispersion clogs the soil pores. Sodicity increases the bulk density, which in turn limits the root perforation. Even at sufficient moisture content, the survival of crops in such soil is very difficult in the absence of subsoil contribution due to low hydraulic conductivity and diffusivity. The hydraulic conductivity is an important property affected by the salinity and sodicity and can serve as the basis for classification for the degree of degradation. Chaudhary (2001) reported that an increase of EC from 0.5 to 5 dS m^{-1} resulted in more than threefold increase in the hydraulic conductivity irrespective of SAR. A threshold electrolyte concentration in the soil solution is necessary for flocculation. Nayak et al. (2004)

Table 22.3 Physico-chemical properties of Sodic Haplusterts at village Sadathala, District Bharuch, in Gujarat

Horizon	Depth (m)	Sand (%)	Silt (%)	Clay (%)	WHC (%)	CEC (cmol kg^{-1})	ESP (%)	$CaCO_3$ (%)	OC (%)
Ap	0.00–0.21	13.3	17.4	69.3	58.1	49.5	19.0	9.9	0.35
Bw1n	0.21–0.53	10.0	18.0	72.0	69.2	50.3	30.2	9.7	0.39
Bss1n	0.53–0.96	7.4	16.8	75.8	72.1	44.0	26.2	11.3	0.41
Bss2n	0.96–1.32	9.0	15.0	76.0	83.2	35.5	26.5	13.1	0.39
BC	1.32–1.70	15.0	25.0	60.0	70.0	46.6	29.4	19.8	0.43

reported that at electrolyte concentration (EC) < 2 dS m^{-1}, Vertisols can be grouped as sodic if the ESP is > 6 and > 10 in clayey and silty clay soils, respectively, and at EC of < 4 dS m^{-1}, Vertisols can be grouped as sodic if the ESP is > 13 and > 21 in clayey and silty clay soils, respectively.

Typical soil profile characteristics of sodic Vertisols from Bharuch district are given in Tables 22.3 and 22.4. In Ukai-Kakrapar command area, about 40% of soils are affected by sodicity problem (Patel et al. 2000). Paddy and sugarcane are the prominent crops in this command area due to availability of perennial irrigation facility, and productivity of these crops is declining due to salinity/sodicity and waterlogging problems (Rana and Raman 1999).

The low organic carbon, high exchangeable sodium, pH, calcium carbonate and toxic concentration of CO_3 and HCO_3 affect adversely the solubility, transformation and availability of the native and applied nutrient elements, especially N, K, Ca, Zn, Fe and Mn, their uptake and cationic balance in plants hindering crop growth and sustainable high productivity in these soils. During high evaporative demands in the semiarid conditions, maintenance of a proper Ca/Mg ratio in the soil solution becomes difficult because Ca^{2+} ions get precipitated as $CaCO_3$ resulting in an increase in the SAR of the soil solution and the ESP of the soil. Although the correlation between carbonate, clay and SAR was not significant, the HCO_3/Ca ratio of the saturation extract has a significant positive correlation with SAR ($r = 0.57$; $p \leq 0.01$, Balpande et al. 1996). This suggests that if this ratio increases, then SAR and ESP will also increase.

22.6.5 Salt-affected Vertisols in the Bara Tract of Gujarat

The prevalence of low to moderate exchangeable sodium is observed in association with soil salinity in some parts of the Bara tract. ESP of the surface soils of the Bara tract (Fig. 22.4) varies from 0.24 to 22.9 with a mean of 4.5 (SD 3.9). The value of ESP to distinguish sodic soils from non-sodic soil is found to be much less in the case of Vertisols as compared to light-textured soils. Accordingly, soils with

Table 22.4 Saturation extract analysis of Sodic Haplusterts at village Sadathala, District Bharuch, in Gujarat

Depth		EC_e	Extractable cations				Extractable anions			SAR
			(meq l^{-1})				(meq l^{-1})			
(cm)	pH	dS m^{-1}	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	$CO_3^{2-} + HCO_3^-$	SO_4^{2-}	(meq $l^{-1})^{1/2}$
0–21	9.1	1.6	4.0	2.7	8.6	0.1	10.0	2.0	3.2	4.7
21–53	9.1	1.9	4.0	2.3	8.7	0.1	13.0	2.0	1.0	4.9
53–96	8.5	4.1	3.0	3.3	30.4	0.1	31.0	2.0	3.0	17.1
96–132	8.4	10.9	7.0	6.5	76.1	0.4	75.0	2.5	13.0	26.0
132–170	8.5	11.6	10.0	7.1	152.0	0.2	156.0	1.5	11.5	58.6

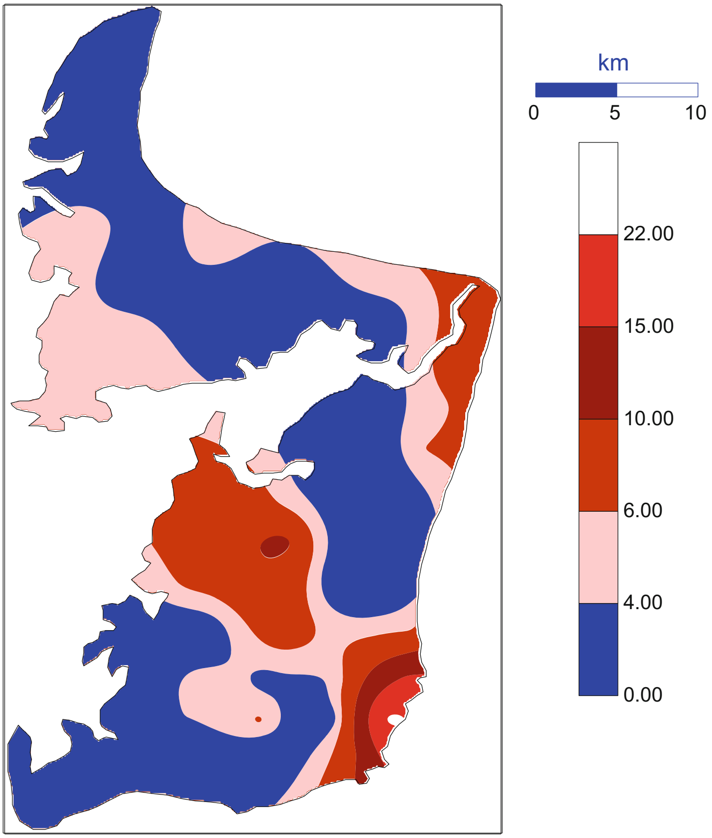


Fig. 22.4 ESP of surface soil of the Bara tract

electrolyte concentration (EC) ≤ 2 dS m^{-1} and ESP > 6 are classified as sodic soils, whereas the soils with EC > 4 dS m^{-1} and the ESP > 13 are termed as sodic soils. Accordingly, most of the surface soils (90%) of the Bara tract are free from sodicity (Fig. 22.4). However, subsoil sodicity is encountered in a fairly large area of the Bara tract. Salinity of these soils shows a greater degree of temporal variation, and the marginal case of 8–10 ESP with soil salinity of 2 dS m^{-1} having temporal variation of 0.5 dS m^{-1} needs no gypsum application, as the increase of electrolyte concentration in some part of the year may lead to the flocculation of soil colloids. The soils of the Bara tract are alkaline; pH varies from 7.2 to 9.3 (Nayak et al. 1999a, 2003).

These soils exhibit higher pH at the lower horizon than the upper layer. This is due to progressively increasing accumulation of $CaCO_3$ in the lower horizon (Figs. 22.5 and 22.6). The lime content of the lower horizon varies from 2.7 to 27.4%. In the lower layer where calcium carbonate has accumulated during pedogenesis, occurrence of sodium bicarbonate and carbonate elevates the soil pH above 9.0, in addition to the toxicity of carbonate and bicarbonate species. This may lead to Fe, N,

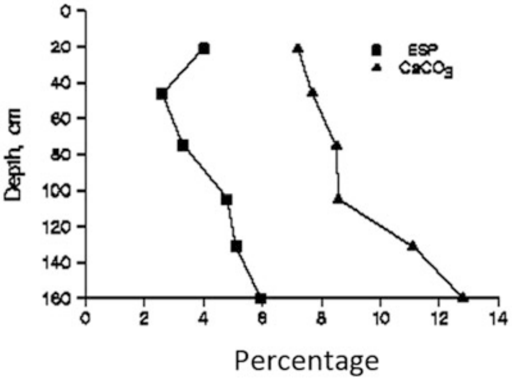


Fig. 22.5 ESP and $CaCO_3$ content of typical Vertisols of Bara tract (Vagra village)

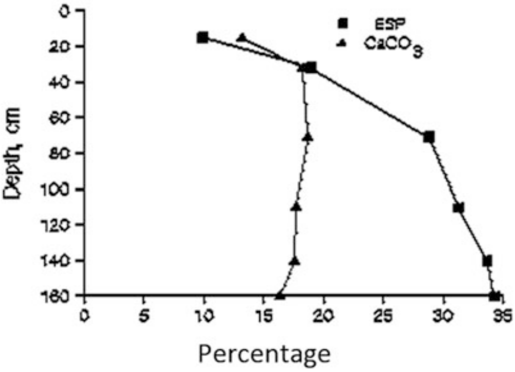


Fig. 22.6 ESP and $CaCO_3$ content of sodic Vertisols of Bara tract (Sadathala village)

Cu, Zn and P deficiency. The subsoil salinity (transient salinity) occurring in dry lands dominated by subsoil sodicity may lead to further complication with rising saline groundwater.

22.6.6 Groundwater

Water quality studies revealed that the 80% of groundwater in coastal and inland saline Vertisols in Gujarat is mostly saline with high SAR values. Highly alkaline and alkaline to marginal alkaline waters were also noticed in certain areas of Gujarat, more so in Bhal area, where water table remains as high as 1.2–1.5 m (Fig. 22.7). Continued extraction of groundwater in coastal region has led to the intrusion of seawater leading to soil salinization and pollution of drinking water supplies. Since degraded soil and water and low soil fertility are the major constraints to increase and stabilize agricultural production, efforts must be made to conserve the vital resources. Rainwater management and the implementation of soil conservation

Fig. 22.7 High groundwater table in Bhal area of Gujarat state

programme hold the key to an ecologically balanced improvement in the quality of rainfed land (Gururaja Rao 2012).

22.7 Management and Use of Saline Vertisols

Saline Vertisols that are widespread in India, by and large, remain fallow during rainy season which subjects them to soil erosion. Vertisols have great potential for productive cropping because their stored water can sustain crops through drought/stress periods. Although the water-holding capacity is high, permeability is slow, and drain ability is poor. The major approaches for reclamation and management of saline Vertisols include:

- Salinity control through ameliorative measures
- Conservation of resources through rainwater harvesting, groundwater-recharging, nutrient and water budgeting and recycling of residues
- Use of saline groundwater in conjunction with conserved rainwater for crop production
- Developing multicropping and integrated farming models for small holdings

22.7.1 Management Practices Devised to Improve Water Regimes

22.7.1.1 Removal of Excess Surface Water

As discussed earlier, the soil physical properties and the soil moisture regime of Vertisols represent serious management constraints. The heavy soil texture and domination of expanding clay minerals result in a narrow soil moisture range between moisture stress and water excess. Tillage is hindered by stickiness when the soil is wet and hardness when it is dry. The susceptibility of Vertisols to waterlogging is the single most important factor that reduces the actual growing period. Excess water during rainy season must be stored for post-rainy use (water harvesting) on Vertisols.

Surface drainage by using alternate broad beds and furrows protects crops from waterlogging of the root zone. The drained water may be stored in small ponds and used for watering vegetables, etc. This technology solves problems on individual farmer's fields, but the soil erosion caused by furrow systems needs to be tackled by bringing the runoff water safely along the grassed waterways to the lowest part of the field. A participatory approach involving all stakeholders is needed to solve this problem on a watershed scale.

22.7.1.2 Storage of Excess Water Within the Watershed

Farm pond technology for storing excess water would serve irrigation needs of the crops. The swell-shrink behaviour of Vertisols poses serious problems and enhances percolation losses. On-farm water management can be attained by having small ponds (discussed later) that provide irrigation needs of vegetables and water requirement of livestock.

22.7.2 Sustainable Agrotechnological Interventions for Saline and Sodic Vertisols

Since the saline Vertisols, particularly in the coastal region, are difficult to manage mainly due to climatic vagaries, suitable technological interventions are needed that comprise (a) identifying salt-tolerant crops, viz. wheat and cotton; (b) conjunctive water use strategies for crop production; (c) use of halophytes with industrial importance; (d) cultivation of forages and halophytic grasses as fodder; (e) use of saline water in fruit crops using pressure irrigation techniques; (f) integration of medicinal and aromatic plants with agroforestry; and (g) farming system approach.

22.7.2.1 Agroforestry for Saline Vertisols

The saline black soils are generally either contemporary or of secondary origin. The contemporary ones exist in the topographic situations under poor drainage conditions. However, the soils that have become sodic due to faulty irrigation practices can be seen in the irrigation command areas. Unlike the alluvial sandy loam soils of Indo-Gangetic plains, their restoration is difficult. Efforts to study the basic, strategic and applied aspects of salt-affected Vertisols have been reported (Chaudhari et al. 2006; Nayak et al. 2004; Gururaja Rao 2015; Gururaja Rao et al. 2001a, b, c, 2004a, b; Gururaja Rao and Singh 1996). Technologies for cultivation of *Salvadora* (tolerates salinity up to 50 dS m^{-1}) for the restoration of highly saline (> 40 dS m^{-1}) soils (Gururaja Rao 1995; Gururaja Rao et al. 2003, 2017) and dill *Anethum graveolens* (tolerates salinity of 4–6 dS m^{-1}) have been adopted by the farmers (Gururaja Rao 2001b).

Long-term experiments indicated *Prosopis juliflora* and *Azadirachta indica* as the ideal species for sodic soils (Tomar et al. 1994; Tomar and Patil 1998; Tomar et al. 1998) and saline Vertisols (Patil 1996). These studies indicated that after 7 years of plantation under *P. juliflora*, pH, EC_e and ESP reduced from 8.8, 4 dS m^{-1} and 35 to 8.5, 1.29 dS m^{-1} and 10, respectively, and under *A. indica* these values reduced to 8.5, 1.3 dS m^{-1} and 14, respectively, in 0–15 cm soil zone.

Aromatic grasses, *Vetiveria zizanioides* and *Cymbopogon martinii*, can be grown easily. *Matricaria chamomilla* can withstand both high pH and ESP. Studies on soils with ESP 25, 40 and 60 indicated gooseberry (*Emblica officinalis*) and *ber* (*Ziziphus mauritiana*) as the most successful fruit plants. Oil-yielding bush, *Salvadora persica*, was grown in combination with *Leptochloa fusca*, *Eragrostis* spp. and *Dichanthium annulatum* forage grasses on saline Vertisol in Gujarat. These grasses could produce on an average 3.72, 1.0 and 1.8 Mg ha^{-1} of forage, respectively. *Salvadora persica* has seed yields ranging from 1.84 to 2.65 Mg ha^{-1} with oil contents 576–868 kg ha^{-1} at different salinity levels in the fourth year (Gururaja Rao et al. 2003, 2013d, 2017). The experiments conducted in sodic Vertisols with ESP 40 growing grasses like *Leptochloa fusca*, *Brachiaria mutica* and *Vetiveria zizanioides* showed that all these grasses performed well and the forage biomass increased during second year. Uptake of sodium by *L. fusca* was the highest followed by *B. mutica* at every stage of cutting. During 3 years these grasses could remove 144.8, 200.0 and 63.5 kg ha^{-1} of sodium from the soil, respectively. Thus, besides producing biomass, silvo-pastoral system helped in amelioration of soil in terms of reducing soil pH, EC and ESP and increasing organic matter.

22.7.2.2 Biomass Species

Hebbara et al. (1992) working with tree species *Casuarina equisetifolia*, *Acacia nilotica*, *Dalbergia sissoo*, *Azadirachta indica*, *Sesbania grandiflora* and *Hardwickia binata* on saline Vertisols in Tungabhadra command area indicated reduction in soil salinity, calcium carbonate and soil-soluble sodium, bicarbonate, chloride, sulphate and sodium adsorption ratio under all the tree species apart from improvement in organic carbon. Tree species such as *A. nilotica* and *C. equisetifolia* with higher biomass production were found to exhibit greater bio-amelioration potential in saline Vertisols and with biomass production. Moderately tolerant species identified included *Albizia amara* and *Pongamia pinnata*. All tree species enriched the soil nutrient pool (N, P and K) and organic carbon and decreased dispersibility of clays. Tree species such as *A. nilotica* and *C. equisetifolia* with higher biomass production exhibited greater bio-amelioration potential in saline Vertisols (Hebbara et al. 1992; Patil et al. 1996, 2005; Manjunatha et al. 2002, 2005). Studies conducted at SK Nagar, Gujarat, indicated that *Eucalyptus* attained the maximum height of 8.15 m among all trees studied. Studies conducted at TNAU indicated that *Albizia lebbeck* under rainfed conditions attained 4.02 m height and 23.90 cm DBH in association with sesamum and sorghum after 4 years.

22.7.2.3 Horticultural Crops

Under horticultural systems, fruit trees such as sapota (*Achras zapota*), guava (*Psidium guajava*), aonla (*Emblica officinalis*), pomegranate (*Punica granatum*), tamarind (*Tamarindus indica*), dates (*Phoenix dactylifera*), karaunda (*Carissa carandas*), ber (*Ziziphus mauritiana*) and jamun (*Syzygium cuminii*) have been

Table 22.5 Performance of guava under drip and surface irrigation in saline Vertisols

EC_{iw} dS m^{-1}	Fruit yield kg per block[a]		Fruit yield kg ha^{-1}		% Gain under drip	Net income ₹ ha^{-1}		B: C ratio	
	Surface	Drip	Surface	Drip		Surface	Drip	Surface	Drip
BAW (0.4)	98.75	96.3	1312	1283	−2.2	6560	6415	1.64	1.60
2	74.40	81.2	992	1082	+9.1	4960	5410	1.24	1.35
4	66.10	75.9	881	1011	+11.4	4405	5055	1.10	1.26
$LSD_{0.05}$	10.39	8.5	123.6	146.6	–	425.2	451.7	–	–

[a] Cost of cultivation taken @ ₹ 4000 ha^{-1}. (30 plants per block) [Cost of plants: ₹ 2000; planting costs: ₹ 1200; On-farm expenses/$year^{-1}$: ₹ 800. During 1st year ₹ 3800 was obtained from 180 plants

Table 22.6 Promising fruit species and varieties for saline Vertisols

Fruit species	Variety
Achras sapota (sapota)	Kalipatti and Cricket Ball
Punica granatum (pomegranate)	Ganesh
Psidium guajava (guava)	Allahabad Safeda
Ziziphus mauritiana (ber)	Gola
Emblica officinalis (aonla, gooseberry)	–

found promising for alkali soils (Singh and Dagar 1998) which are also suitable for sodic Vertisols. They had compared planting costs of these fruit species both by pit planting and auger-hole methods and found that the latter is significantly less cost intensive, i.e. ₹ 20,396 ha^{-1} (cost based on reported year), when compared to the pit planting method (₹ 42,214 ha^{-1}). Studies conducted on saline Vertisols using saline water under drip system and conventional basin irrigation showed that pomegranate was much more beneficial in terms of income generation (Gururaja Rao and Khandelwal 2001), fruit yield, net income and better benefit/cost ratio under drip irrigation system than surface/basin irrigation (Table 22.5). Performance of fruit species on saline Vertisols under Tungabhadra canal command has also been reported by Hebbara et al. (2002).

22.7.2.4 Ideal Silvi-horti-agricultural System

Inference was drawn from the studies carried out on alkali soils that system consisting of guava+subabul (*Leucaena leucocephala*) +*Eucalyptus tereticornis* was ideal for sodic soils. The fruit species which were suitable for saline Vertisols included *Carissa carandas*, *Ziziphus mauritiana*, *Emblica officinalis*, *Syzygium cumini* and *Psidium guajava* (Table 22.6). Experiments on sapota and guava with saline water irrigation on saline Vertisols indicated the use of saline water of EC_{iw} 4–6 dS m^{-1} using drip irrigation was found effective (Gururaja Rao and Khandelwal 2001; Gururaja Rao et al. 2009, 2012). Fruit-bearing *E. officinalis*, *C. carandas* and *Z. mauritiana* and Bael (*Aegle marmelos*) withstand drought as well as salinity. These can be cultivated with success irrigating with water up to 12 dS m^{-1}. These along with guava (*Psidium guajava*) and *Syzygium cumini* could be grown on highly alkali soil (pH up to 9.8) with application of amendments (gypsum) in auger holes. Pomegranate (*Punica granatum*) is salt-tolerant but does not withstand waterlogging.

22.7.2.5 Halophytes of Industrial Importance for Saline Black Soils

Saline agriculture is a prospective area of research where the genetic resources of halophytes and salt-tolerant plants could be utilized for producing human and animal diet and a variety of other raw materials on saline wastelands using saline irrigation waters (Dagar et al. 2001, 2006a, b; Dagar 2018). The sustainable cultivation of halophytes and other salt-tolerant crops can serve commercial purposes without land degradation. Many halophytes combine high biomass and high protein or mineral levels with outstanding ability to a wide range of environmental stresses (Flowers and Colmer 2008; Flowers et al. 1986; Arora et al. Arora Sanjay Bhuva et al. 2013; Dagar 2018). Use of saline and brackish water resources has been recommended for growing salt-tolerant crops as source of food, fuel, fibre, fodder and medicine (Dagar 1995a, b, 2003, 2005, 2018; Rozema and Flowers 2008). Potential candidate species for cultivation on saline black soils (saline Vertisols) and their uses are briefly described below.

22.7.2.5.1 Cultivation of *Salvadora persica* (Meswak): A Potential Life-support Plant for Highly Saline Vertisols ($EC_e > 30$ dS m^{-1})

For the management of coastal moderately to highly saline Vertisols, an agrotechnology for cultivating economically important and highly salt-tolerant *Salvadora persica* (Meswak, Jaal; Fig. 22.8), a facultative halophyte and source of seed oil, has been evolved (Gururaja Rao et al. 2003, 2017). This species is of medicinal value as its bark contains an alkaloid called salvadoricine. The seeds are good source of nonedible oil rich in C-12 and C-14 fatty acids having immense applications in soap and detergent industry (Gururaja Rao 1995, 2015; Reddy et al. 2008). *Salvadora persica* being a large, well-branched evergreen shrub or small tree

Fig. 22.8 *Salvadora persica* on highly saline black soils; salts are visible on soil in background

Table 22.7 Cost of cultivation of *Salvadora persica* on highly saline black soil (cost taken per hectare of plantation)

Field operations (input costs)	Cost (₹)
Field preparation (by tractor)	500
Pitting (625 pits of 30 cm × 30 cm × 30 cm)	625
Cost of saplings at ₹ 0.90 per plant	565
Planting	50
Irrigation during first year (saline water)	150
Digging of pit of 2.5 × 2.0 × 1 m (for saline water)	300
Fertilizer at 50 g DAP per plant and FYM	300
Plant basin making at ₹ 0.35 per plant	220
Misc. (gap filling at 5%)	50
Total	2760

Source: Gururaja Rao et al. (2003)

Table 22.8 Seed production and economic returns of *Salvadora* plantation on highly saline black soils ($EC_e > 55$ dSm^{-1})

Year	Seed yield (Mg ha^{-1})	Returns (₹ ha^{-1})		Cost/benefit ratio
		Gross	Net	
I Year	Nil	Nil	Nil	Nil
II Year	0.725	3625.00	365.00	10.03
III Year	0.978	4890.00	4340.00	0.13
IV Year	1.58	7900.00	7250.00	0.09
V Year	1.838	9190.00	8440.00	0.09

Source: Gururaja Rao et al. (2003)

has the potential for re-greening the highly saline Vertisols that cannot be put under arable farming (Gururaja Rao et al. 1999a, b).

Earlier reports by Gururaja Rao et al. (2003) indicated that the saplings could be raised using saline water of 15 dS m^{-1}, an advantageous feature under limited fresh water availability. Cost of cultivation (as in reporting year) under field conditions comprising nursery raising comes to ₹ 2760 ha^{-1} (Table 22.7) in the first year. By the fifth year, the plants would yield about 1800 kg ha^{-1} (Table 22.8, Fig. 22.9), thus, giving net returns to a tune of ₹ 8400 ha^{-1}. Thus, this species, while giving economic returns from the highly saline black soils with salinity values up to 50 dS m^{-1}, also provides eco-restoration through environmental greening (Gururaja Rao et al. 2003, 2004a, b).

A spacing of 4 m × 4 m has been found ideal for planting on saline black soils (Gururaja Rao et al. 2004a, b). A bankable refinancing model for saline Vertisol restoration using *Salvadora persica* was developed by CSSRI, Bharuch and NABARD. Cultivation of *S. persica* up to 4 years resulted in slight decline in soil salinity when compared to the pre-planting salinity. Changes in surface salinity are partly attributed to the ability of plants to absorb the salt and partly due to root activity which improves the physical properties of the soil. However, the magnitude of fluctuation in salinity was not much at lower layers. The groundwater table might be contributing to such small changes at lower depths. Reduction in salinity by the

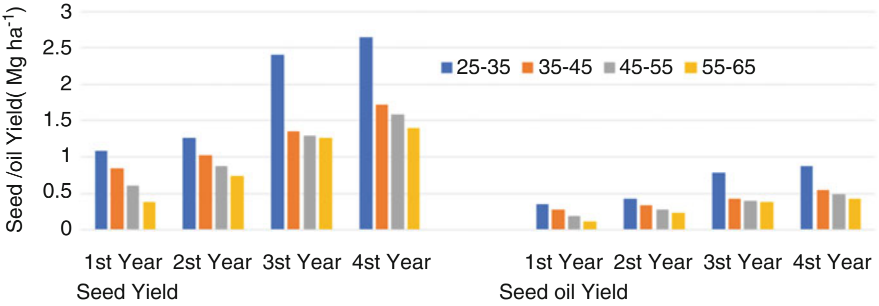


Fig. 22.9 Seed and oil yield in *Salvadora persica* grown at different salinities

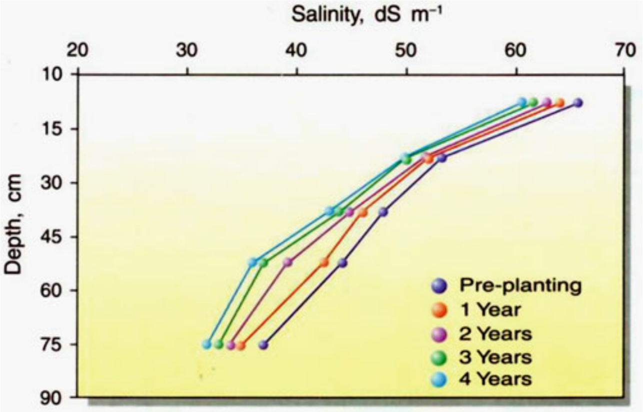


Fig. 22.10 Soil salinity variations over the years under *S. persica* grown on highly saline black soil (EC_e 55–65 dS m^{-1} range)

fourth year onwards (Fig. 22.10) further forms a basis to take up intercropping with less tolerant crops/forages, resulting in wider adoption of this intervention in coastal and inland saline Vertisols of Gujarat.

22.7.2.6 Halophytes as Source of Food, Feed and Fuel: Alternate Interventions

The glasswort (*Salicornia bigelovii*) is a leafless annual salt-marsh plant (Fig. 22.11) with green jointed and succulent stems producing seeds that are 30% oil and 35% protein; the oil is similar in fatty acid composition to safflower oil and hence suitable for human consumption. The coastal salt-marsh succulent *Salicornia bigelovii* is extremely salt-tolerant and one of the most versatile halophytes currently under commercial production. It is now being harvested and used as salad (greens), while the seed forms a good source of high-quality edible oil; the residual meal provides superior feed for livestock and shrimp/fish. In addition, *Salicornia* stem and straw can be utilized as cut hay in mixed feeding regimes, manufactured into pressed board for construction purposes or in paper making.

Fig. 22.11 *Salicornia bigelovii*

Salicornia is also cultivated on saline Vertisols with lower clay regimes using seawater for irrigation. To make *Salicornia* cultivation economically viable, besides oil and vegetable tips, a process to produce herbal salt from the waste biomass after removing the seeds for oil was developed. The herbal salt contains several important nutrients besides low levels of sodium, which is considered to be beneficial for heart patients.

Studies by Pandya et al. (2006) revealed that application of nitrogen (N) up to 100 kg ha^{-1} had significantly increased the seed yield (29% and 87%) and plant biomass (29 and 51%), over 75 and 0 kg N ha^{-1}, respectively. Plant characters, canopy spread, spike length, number of segments and harvest index were also found increased with the increase in N application. An application of 75 kg P_2O_5 ha^{-1} was also found significant with an achievement in higher seed yield production (48%) and number of spike segments (43%) over the control. The interaction study between the applied doses of N × P was found significant at highest fertilizer levels ($N_2 \times P_2$), and they produced maximum seed yield over the control but remain at par in case of plant biomass. The plant nitrogen content in biomass (spike+seed) though found increased with N application has remained at par in case of P application (Table 22.9). Nitrogen and potassium content and uptake were found increased significantly with N application. The plant density had a significant effect on yield, biomass and other important yield attributes. Optimum plant density of 278 plants 10 m^{-2} and 100 kg N ha^{-1} and 75 kg P_2O_5 ha^{-1} had good impact on improvements of vegetable biomass and oil of *Salicornia brachiata* (Fig. 22.12).

Commercial cultivars of *Salicornia bigelovii* have been reported to produce seed of 2 Mg ha^{-1} with an overall biomass production of 20 Mg ha^{-1}. When mixed with traditional fodder, the residual meal makes for an excellent feed supplement. A number of other species of *Salicornia* such as *S. rubra*, *S. europaea*, *S. herbacea*, *S. peruviana* and *S. virginica* possess similar commercial potential. Select varieties of *S. brachiata* are now being cultivated in the deserts of India for value-added by-products like vegetable salt (Attia et al. 1997).

Table 22.9 Effect of phosphorus on yield attributes in *Salicornia brachiata*

Phosphorus levels	Seed yield	Dry biomass	Plant height	Canopy spread	Main branches	Spikes per branch	Spike length	Segments	HI
	kg ha^{-1}	kg ha^{-1}	cm	cm	no.	no.	cm	no.	%
P0	571.6	5192	30.10	123.9	33.2	424.2	9.80	5.7	24.9
P_1	609.0	6016	31.70	125.9	33.3	423.8	11.00	5.9	28.9
P_2	846.2	7144	30.20	122.3	34.1	564.2	11.40	8.2	41.8
SEm	88.10	759.2	0.51	4.51	2.91	52.06	0.56	0.49	13.1
LSD ($p \leq 0.05$)	215.6	NS	NS	NS	NS	NS	NS	1.72	NS

Source: Pandya et al. (2006)
HI harvest index, *NS* non significant

22.7.2.7 Cultivation of Seed Spice, Dill (*Anethum graveolens*), as an Ideal Intervention for Moderately Saline Black Soils

Dill, *Anethum graveolens* (Fig. 22.12), a nonconventional seed spice crop, has been identified as potential crop for cultivation on saline black soils having salinity up to 6 dS m^{-1}. It has multiple uses, viz. pot herb, leafy vegetable, seeds used as condiments and seed oil for aromatic and medicinal purposes. The herb contains vitamin C as high as 121.4 mg100 g^{-1}. The seed oil and its emulsion in water (dill water) are considered to be aromatic, carminative and effective in colic pains and possess antipyretic and antihelminthic properties. The crop responds well to saline water irrigation. Three critical stages for saline water irrigation have been noticed, i. e. vegetative, flowering and seed formation stage. The cost of cultivation comes to ₹ 6000 ha^{-1}, and the crop would yield net returns of ₹ 16,500 ha^{-1}. The benefit/cost ratio works out to be 2.75. This crop, thus, would help farmers of the region to go for the second crop in the *rabi* (winter) season on saline Vertisols (Tables 22.10, 22.11 and 22.12; Gururaja Rao et al. 2001a, 2013d).

Thus, it can be concluded that nonconventional seed spice crop like *dill* can be grown using residual moisture resulting in 260 kg ha^{-1}seed yield. This crop forms an ideal option for saline Vertisols of Gujarat state, which by and large faces water scarcity during *rabi* season (Gururaja Rao et al. 2013d). Under saline water irrigation, crop would yield net returns of ₹ 16,500 ha^{-1} with ₹ 6000 per hectare as cost of cultivation. The benefit/cost ratio works out to be 2.75. Thus, dill crop can be taken up using residual moisture and/or with saline groundwater.

Fig. 22.12 Dill (*Anethum graveolens)* on saline Vertisols under saline water irrigation

Table 22.10 Cost of cultivation of dill on saline black soils and economic returns

Items of expenditure	Cost (₹)
Field preparation	1200
Seed material	150
Seed treatment and sowing	300
Fertilizers	800
Application of fertilizer	200
Interculture and weeding	350
Irrigation*	1500
Harvesting and threshing	1000
Miscellaneous	500
Total	6000
Returns	
Yield of dill, 0.75 Mg ha^{-1}	
Gross returns at ₹ 30,000 Mg ha^{-1}	22,500
Net returns (₹)	16,500

Table 22.11 Seed yield of dill (kg ha^{-1}) as influenced by different salinity levels under different farm sites

Salinity (dS m^{-1})	Khanpur	Warsada	Bamangam
2–4	374	409	316
4–6	303	225	237
6–8	234	176	164
8–10	195	136	156
LSD ($p \leq 0.05$) farm, NS; salinity, 0.13; farm × salinity, NS			

Source: Gururaja Rao et al. (2001a)
NS non significant

Table 22.12 Effect of quality and number of irrigation waters on yield of dill (kg ha^{-1}) on saline black soils

	One irrigation		Two irrigations		Three irrigations	
Salinity (dS m^{-1})	Seed	Stover	Seed	Stover	Seed	Stover
BAW	784	2352	834	2500	914	2651
4	650	1958	815	2526	906	2808
8	354	1200	417	1334	567	1814
12	209	689	292	992	367	1212
LSD ($p \leq 0.05$)	No. of irrigations (I), 30; quality of water (Q), 33; I × Q, 81					

22.7.2.8 Forage Grass Cultivation on Saline Black Soils as Another Alternate Intervention

Agriculture and animal husbandry in India are interwoven and form an integral part of rural living. Due to ever-increasing population pressure, arable land will mainly be used for food and cash crops, leaving little chance of having good-quality arable lands for fodder production. Thus, saline/sodic lands provide a good avenue to increase the

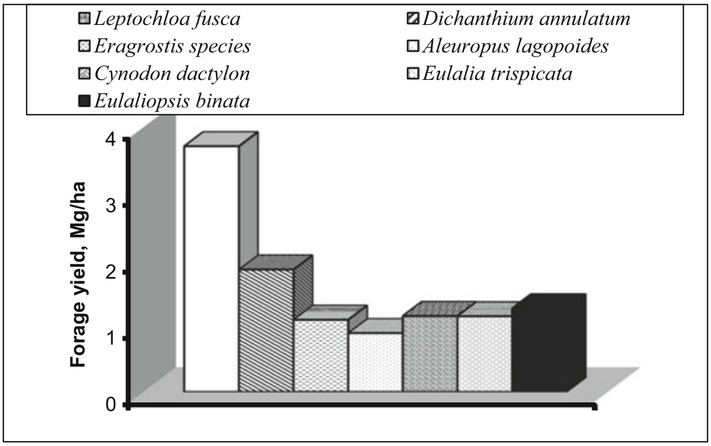


Fig. 22.13 Forage yield of grasses on saline black soils (EC$_e$ 14.6 dS m^{-1}). (Source: Gururaja Rao et al. 2001b)

fodder production. Forage grasses such as *Leptochloa fusca*, *Cynodon dactylon*, *Aeluropus lagopoides*, *Dactyloctenium sindicum*, *Paspalum vaginatum*, *Chloris gayana*, *Echinochloa crusgalli*, *E. colonum*, *Eragrostis tenella*, *Dichanthium annulatum* and *Brachiaria mutica* are the predominant ones in coastal saline black soils (Dagar 2005). Many of these perform well on saline Vertisols (Fig. 22.13). Forage grasses like Kallar grass (*Leptochloa fusca*), Rhodes grass (*Chloris gayana*), para grass (*Brachiaria mutica*) and *Panicum* spp. are highly salt-tolerant and high biomass yielders. While *Prosopis juliflora* and Kallar grass -based silvo-pastoral system has been found highly promising for firewood and forage production on sodic soils (Singh 1995; Singh and Dagar 2005), *Salvadora persica* with Kallar grass and/or *Dichanthium annulatum* has been found ideal for saline Vertisols (Gururaja Rao 2001c). Singh and Dagar (1998, 2005) and Singh et al. (1993, 2014) reported a silvo-pastoral system comprising *Prosopis* with Kallar grass was found ideal and highly remunerative in the early 4 years of establishment. Tree species like *Acacia nilotica*, *Eucalyptus tereticornis* and *Parkinsonia aculeata* on ridges and Kallar grass in trenches were found successful (Grewal and Abrol 1989). Performance of Kallar grass in furrow system has been found beneficial on saline Vertisols (Gururaja Rao et al. 2001b; Gururaja Rao et al. 2005, 2011). Agrotechnology for the cultivation of forage grasses *Dichanthium annulatum* and *Leptochloa fusca* was evaluated and found promising on saline Vertisols of 8–10 dS m^{-1}. Application of nitrogen at 46 kg ha^{-1} as urea increased the forage yield by about 70% in *Dichanthium annulatum* (Gururaja Rao et al. 2001b, d). The quality of forage of this grass is better, and it is also highly salt-tolerant (Gururaja Rao et al. 2001b) and has been found to possess a well-defined salt compartmentation, wherein the roots act as a potential sink for toxic ions like Na$^+$ and Cl$^-$ making the shoots relatively salt-free. *Dichanthium annulatum* and *Leptochloa fusca* in a ridge-furrow planting system with 50-cm-high ridge and 1 m between midpoints of two successive ridges were found ideal in saline

Table 22.13 Growth and yield of forage grasses under ridge and furrow planting system (Salinity of the saturation extract of soil (0–30 cm), 15.4 dS m^{-1})

	Height, m		Tillers plant^{-1}		Green forage yield, Mg ha^{-1}	
Grass species	Ridge	Furrow	Ridge	Furrow	Ridge	Furrow
Leptochloa fusca	1.18	1.02	10.62	9351	3.17	3.73
Dichanthium annulatum	0.91	0.74	6.41	5.32	1.85	1.76
LSD ($p \leq 0.05$)		Height		Tillers		Yield
Planting method		0.12		0.91		NS
Grass species		0.16		1.53		0.82
Planting method × grass species		NS		2.24		NS

Source: Gururaja Rao et al. (2001b)

Table 22.14 Effect of nitrogen on growth and forage yield of forage grosses

	Height, m		Tillers plant^{-1}		Green forage yield, Mg ha^{-1}	
Grass species	+ N	− N	+ N	− N	+ N	− N
Leptochloa fusca	1.39	0.99	12.54	4.46	3.21	2.13
Dichanthium annulatum	1.01	0.87	10.24	7.38	2.24	1.32
LSD ($p \leq 0.05$)		Height		Tillers		Yield
Planting method		0.13		3.11		0.88
Grass species		0.22		2.32		0.55
Planting method × grass species		NS		NS		NS

Source: Gururaja Rao et al. (2001b)

Vertisols having salinity up to 8–10 dS m^{-1} (Table 22.13). For maximizing forage production on saline black soils, *Dichanthium* on ridges and *Leptochloa* in furrows form ideal proposition. Nitrogen given at the rate of 45 kg ha^{-1} (in the form of urea) at the time of rooted slip planting boosts forage production (Table 22.14) and improves forage quality traits.

22.7.2.8.1 Halophytic Grasses on Moderately Saline Black Soils

Halophytic forage grasses, viz. *Aeluropus lagopoides* and *Eragrostis*, have been found ideal for saline agriculture on saline black soils. Of these two, *Aeluropus* was found to possess better forage qualities and salt removal ability. These grasses responded well to saline water up to 30 dS m^{-1} and thus form suitable for cultivation on coastal saline Vertisol with plenty of saline groundwater resources (Ahmed et al. 2011; Gururaja Rao et al. 2013d). The green forage yield of these halophytic grasses is depicted in Fig. 22.14. The data indicated that *Eragrostis* spp. had higher forage yield under field conditions when compared to *Aeluropus lagopoides* even at salinity of 14.6 dS m^{-1}. Working with *Eragrostis tef*, Asfaw and Danno (2011) reported that tef varieties are most affected by salinity than tef accessions.

Increase in these forage quality traits with increase in salinity of irrigation water was noticed in both the grass species indicating their higher production at higher

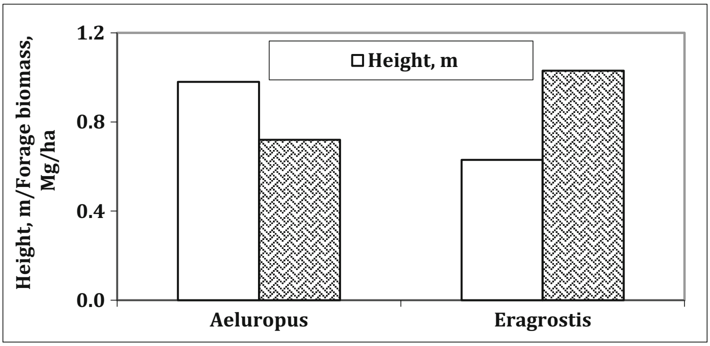


Fig. 22.14 Growth and forage yield of halophytic grasses grown on saline black soil

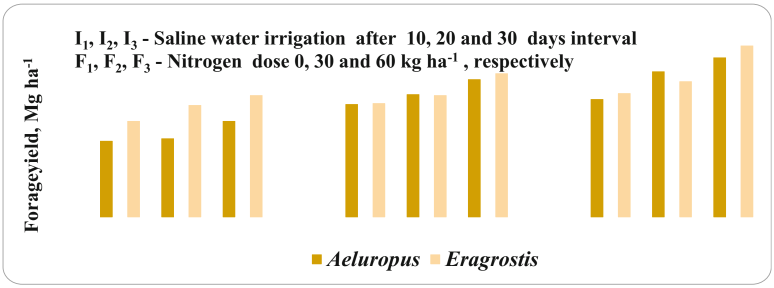


Fig. 22.15 Forage yield of grasses as influenced by nitrogen

salinity levels. Crude fibre is a mixture of cellulose, hemicellulose and lignin gives strength to and its higher content indicated higher photosynthate production. Higher ash content of *Aeluropus lagopoides* can be ascribed to higher mineral uptake as reported in other grasses.

22.7.2.9 Effect of Nitrogenous Fertilizer on Growth and Forage Yield of Grasses

Application of nitrogen coupled with saline water irrigation has been found to enhance forage biomass (Fig. 22.15). Moreover, nitrogen being the most limiting nutrient on saline Vertisols, its supplementation resulted in significant increase in forage yield of both *Aeluropus* and *Eragrostis*. Of the two, *Eragrostis* found to have higher growth, tillers and forage yield with 60 kg ha^{-1} N application when saline water was applied at 15 days interval (Table 22.15). However, no significant differences were noticed when the grasses were irrigated at 15 and 30 days interval, indicating by irrigating once in 30 days, even saline water can be saved by 50%, which becomes handy in saline agriculture programmes. Nitrogen given at 60 kg ha^{-1} though slightly enhanced forage yield with three irrigations when compared to two irrigations, and thus by forgoing slight forage loss, saline water can be saved up to 33%.

Table 22.15 Effect of nitrogen on biomass (Mg ha^{-1}) of halophytic grasses with saline water

	Aeluropus lagopoides			*Eragrostis* species		
Irrigation	Nitrogen, kg ha^{-1}					
	0	**30**	**60**	**0**	**30**	**60**
I_1	1.01	1.24	1.29	1.12	1.25	1.34
I_2	1.10	1.28	1.36	1.19	1.28	1.41
I_3	1.15	1.31	1.41	1.22	1.31	1.44
LSD ($p \leq 0.05$)	Nitrogen (N), 0.18; irrigation (I), 0.09; N × I, 0.11			N, 0.08; I, 0.12; N × I, 0.11		

I_1, I_2 and I_3 indicate the frequency of irrigation after 10, 20 and 30 days, respectively

22.7.2.10 Other Halophytes as Source of Fodder, Forage and Green Manure

The potential of halophytic grasses as fodder was also investigated by Pasternak (1990) and Bustan et al. (2005). Indeed, although less salt-tolerant than species of *Atriplex*, the ash content of *Distichlis spicata* accessions never exceeded 11% of the dry matter, about half the amount found in the salt-accumulating chenopods, highlighting its potential as a fodder crop (Bustan et al. 2005). The protein content of *D. spicata* varied widely between the accessions and ranged from a minimum of 9.2% to a maximum of 18.9% of dry matter, similar to the protein content reported by Pasternak (1990) for *Atriplex nummularia*. In coastal Pakistan, cultivation of the halophytic grass *Leptochloa fusca* (Kallar grass) not only resulted in high productivity of 20 Mg ha^{-1} from 4 to 5 cuts per year (Mahmood et al. 1994) but also improved the soil conditions, showing increased vegetation growth after a 5-year period (Hollington et al. 2001). The anatomical adaptation of grasses for salt secretion evidently contributes to the maintenance of low leaf salt levels and relatively low (compared with those existing in dicotyledonous halophytes) Na/K ratio (Flowers and Colmer 2008). Liphschitz et al. (1974) reported the existence of active salt-secreting glands on the leaves of salt-tolerant grass species, namely, Rhodes grass (*Chloris gayana*), para grass (*Brachiaria mutica*) and Guinea grass (*Panicum maximum*). *Pennisetum clandestinum* and *Sporobolus virginicus* were cultivated for their potential as salt-resistant ground cover and pasture plants with good nutritive properties (Table 22.16). Root as well as shoot growth decreased significantly when plants were irrigated with saline water, but reduction among salinity levels up to 16 dS m^{-1} was not significant (Ventura et al. 2015).

Studies on saline Vertisols in Tungabhadra command in Karnataka of India with four perennial forage grasses, viz. Guinea grass, grazing Guinea grass, para grass and Rhodes grass, on natural soil salinity gradient wherein soil salinity varied from < 4 to > 20 dS m^{-1} indicated that the forage yield of Rhodes (26.7 Mg ha^{-1}), para (28.8 Mg ha^{-1}) and grazing Guinea (28.3 Mg ha^{-1}) grasses were higher at soil salinity of <4 dS m^{-1}. At soil salinity of 4–8 dS m^{-1}, there was $<10\%$ reduction in forage yield of Rhodes (24.2 Mg ha^{-1}), para (25.2 Mg ha^{-1}) and grazing Guinea (27.2 Mg ha^{-1}), whereas it was 50% in Guinea (20.2 to 10.2 Mg ha^{-1}) grass. Further, drastic reduction in forage yield of all the forage grasses was observed in

Table 22.16 Yield of perennial grasses irrigated with brackish and reclaimed water

	Green forage yield, Mg ha^{-1}			
Soil EC$_e$ range, dS m^{-1}	Rhodes grass	Para grass	Grazing Guinea	Guinea grass
<4	26.67	28.78	28.33	20.22
4–8	24.17	25.22	27.21	10.22
8–12	17.23	10.21	17.90	10.74
12–16	17.52	15.14	14.11	6.01
>16	13.19	13.89	14.59	10.93

Table 22.17 Soil salinity and biomass yield of forage grasses on saline Vertisols of Tungabhadra command

Species	Irrigation water	Fresh weight (t ha^{-1}) month	Dry weight (%)	Dry weight (t ha^{-1}) month
Sporobolus virginicus	Reclaimed	4.20 ± 2.18	66.87	2.81 ± 1.46
	Brackish	5.58 ± 2.68	45.88	2.56 ± 1.23
Pennisetum clandestinum	Reclaimed	7.19 ± 1.20	41.17	2.96 ± 0.49
	Brackish	9.92 ± 2.61	33.57	3.33 ± 0.88

The salinity of the brackish water ranged between 7 and 10 dS m^{-1}. The salinity of the reclaimed sewage was 2–3 dS m^{-1}

the soil salinity range of EC$_e$ 8–12, 12–16 and > 16. Rhodes, para and grazing Guinea grasses can be successfully grown in the salinity range of EC$_e$ 4–8 dS m^{-1} (Table 22.17).

22.7.2.11 Cotton-pulse Intercropping: Economically Viable Intervention for Moderately Saline Black Soils

Farmers of the Bara tract in Gujarat and parts of Saurashtra who take cotton as rainfed monocrop do face crop losses due to salinity occurrence at later stages of crop growth. Under such situations, intercropping with pulses provides remuneration in the event of failure of cotton crop. On-farm trials have indicated that cotton-cluster bean intercrops (Fig. 22.16) proved to be beneficial on moderately saline black soils having salinity of 4–6 dS m^{-1}. Cotton intercropped with cluster bean produced cotton seed yield at par with that of sole cotton. Nitrogen application at 80 kg N ha^{-1} significantly increased the seed cotton yield under saline conditions (Table 22.18). Cluster bean while improving the fertility of the soil provides an insurance against the failure of cotton crop.

About 165 ha of land of the Bara tract particularly in Vagra and Amod talukas, the farmers have been adopting the cotton intercropped with pulse technology for maximizing the production. The system would fetch about ₹ 16,000 per hectare from cotton, and further the pulses due to their nitrogen-fixing ability enrich the soils with nitrogen. Cotton as well as pulses can be taken as rainfed crops, providing saline water irrigation, and if available further boosts the crop yields. Use of saline water in cotton has been proved beneficial on saline black soils (Gururaja Rao et al. 2013d).

Fig. 22.16 Cotton-pulse intercropping on saline Vertisols of Bara tract (Gujarat)

Table 22.18 Performance of cotton intercropped with pulses under different levels of fertilizers on moderately saline Vertisols of Bara tract

Treatments	Seed cotton yield, kg ha^{-1}	Treatments	Seed cotton yield, kg ha^{-1}
Main-plot treatments		Sub-plot treatments	
Inter crops (pulses)		Fertilizer levels (kg ha^{-1})	
		N + 40 kgP_2O_5 ha^{-1}	
Sole cotton	572.0	Control	355.1
Cotton + black gram	532.7	20	440.3
Cotton + cluster bean	559.3	40	537.6
Cotton + soybean	556.9	60	626.1
SEm (±)	9.3	80	676.3
LSD ($p \leq 0.05$)	22.7	100	685.8
		SEm (±)	15.2
		LSD ($p \leq 0.05$)	30.7
Coefficient of variation		6.7%	

Source: CSSRI Annual Report (2003–2004)

22.7.2.12 Cultivation of Salt-Tolerant Crops as Ideal Intervention for Coastal Saline Vertisols

22.7.2.12.1 Desi (Local) Cotton on Coastal Saline Vertisols

Sustainability of an ecosystem rests on the scientific management based on a sound database. For the management of saline Vertisols of Southern and Saurashtra regions of Gujarat state of India, the use of salt-tolerant crop varieties has been considered an ecologically and economically viable option. To overcome the constraints of saline soil and groundwater, the use of salt-tolerant varieties is an effective, economic and eco-friendly approach in management of saline Vertisols. It has been used as a biological approach to manage salt-affected lands. Although cotton is classified as one of the most salt-tolerant crop and considered as a pioneer crop in reclamation of saline soils (Maas 1986), its tolerance to salinity is far from that of halophytes (Dong 2012). Therefore, growth and yield reduction are inevitable under high salinity, which often reduces vegetative growth to a greater degree with more reduction in shoots than roots (Ashraf 2002; Dong 2012). Research conducted in this direction resulted in identification of ideal *herbaceum* cotton cultivars like G. Cot 23, G. Cot DH 7, G. Bav 109 and G. Bav 120 (Gururaja Rao et al. 2013a, b, c). Studies by Gururaja Rao et al. (2013c) with diverse cotton accessions clearly indicated that on saline soils of Bara tract and Bhal area, *herbaceum* cottons showed better adaptability and seed cotton yield under rainfed conditions. Seed cotton yield obtained from the farmers' fields is found at par with that of experimental yield (Table 22.19).

In Vertisols with high sub-surface salinity (Nayak et al. 2003), *herbaceums* and *arboreums* showed seed cotton yields comparable to those obtained under well-managed experimental sites suggesting the possibility of their expansion in other saline areas (Fig. 22.17). In view of their low water requirements, minimum or no-pest problems (Gururaja Rao et al. 2013c) and satisfactory yields, *desi* (local) cottons are preferred by farmers across different farm units in the coastal Gujarat where the salinity at harvest ranged from 7.4 to 8.8 dS m^{-1}. A strong negative relation ($r^2 = 0.8821$) between soil salinity and seed cotton yield was noticed. Seed cotton yield dropped below 1.7 Mg ha^{-1} only at 9 dS m^{-1} (Fig. 22.18). As compared to hybrids and Bt lines, *desi* cottons possessed higher salt tolerance and

Table 22.19 Performance of desi cottons in Bara tract area

District/taluka	Village	Crop	Mean yield Mg ha^{-1}	Soil salinity dS m^{-1}
Bharuch/Jambusar	Kalak	G. Cot 23	1.78	9.20
	Magnad	G. Cot 23 (*herbaceum*)	1.89	8.40
		G. Bav 120 (*arboreum*)	1.68	8.45
	Bojadara	G. Cot 23	1.84	8.82
		G. Bav 120	1.76	8.75
CSSRI farm	Samni	G. Cot 23	1.91	7.86
		G. Bav 120	1.80	8.02
		Total average	1.81	8.50

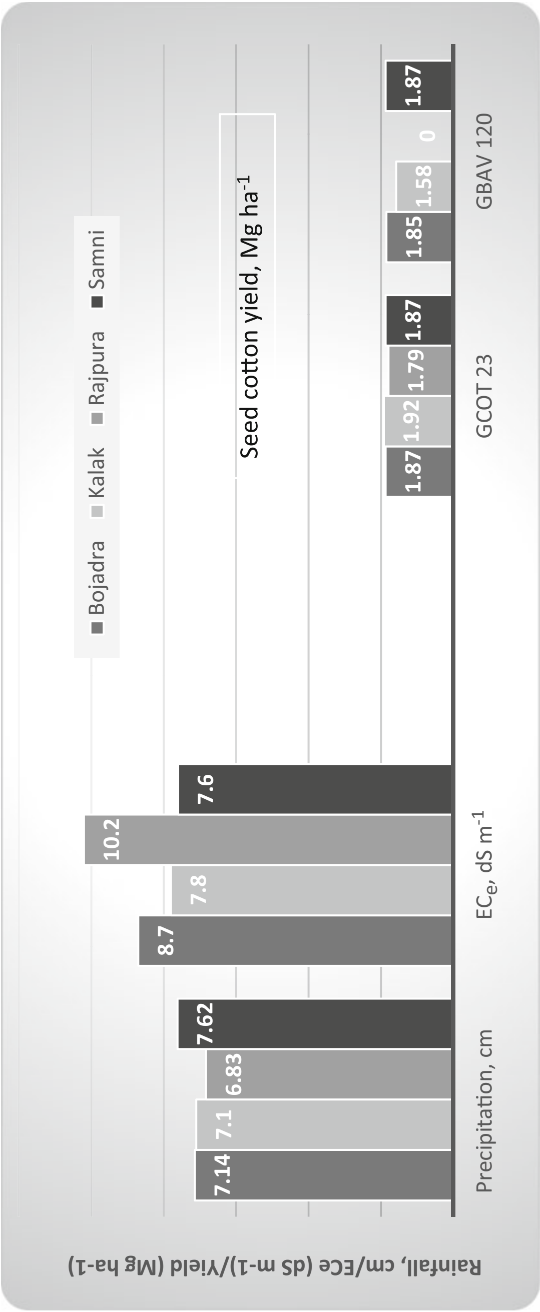


Fig. 22.17 Rainfall (pptn), soil salinity (EC$_e$) and seed cotton yield (Mg ha^{-1}) in South Gujarat

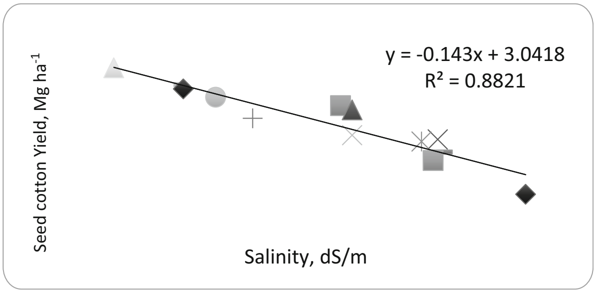


Fig. 22.18 Relation between soil salinity and seed cotton yield

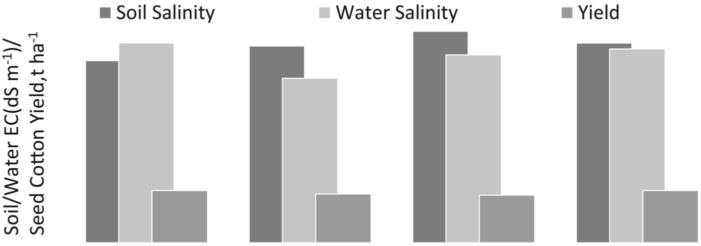


Fig. 22.19 Performance of cotton (G. Cot 23) in Junagadh district (NGO Partner: VRTI, Rajula)

showed lowered yield drop at salinity more than 6 dS m^{-1} (Gururaja Rao et al. 2013a). Unlike *hirsutums*/hybrids which have shallow root system and shortened lifespan (July to October) with high water requirement, *desi* cottons have deep root system and longer life cycle (July to March). The low amount of water by *desi* cottons rendered them as ideal ones for rainfed saline Vertisols (Gururaja Rao et al. 2013b, c, 2016).

In Saurashtra, cultivation of *desi* cotton (G. Cot 23) on saline Vertisols resulted in seed cotton yield in the range of 1.62–1.78 Mg ha^{-1} at salinity of 6.2–7.2 dS m^{-1} (Fig. 22.19). When compared to the soils of South Gujarat or Bhal area, the soils of Saurashtra are of clay-loam type and needed more irrigations, which, however, have not resulted in higher root zone salinity.

The continued efforts resulted in expanding the cultivation of salt-tolerant *herbaceum* cotton (G. Cot 23) in coastal areas of Gujarat. The seed cotton yield obtained under different NGO clusters is depicted in Fig. 22.20. Cultivation of desi cottons lines gained momentum over hybrids or Bt lines, mainly due to low input costs and their better response to saline water irrigation (Gururaja Rao et al. 2013a, b, c, d).

22.7.2.12.2 Wheat on Coastal Saline Vertisols

The Central Soil Salinity Research Institute, Karnal, has developed salt-tolerant wheat varieties (KRL 1–4, KRL 210, KRL 213 and KRL 19), which are popular

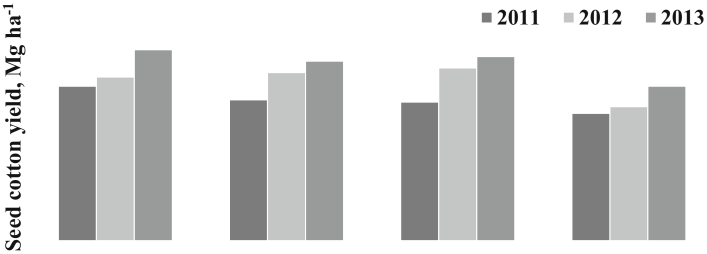


Fig. 22.20 Seed cotton yield in South Gujarat and Saurashtra during 2011–2013

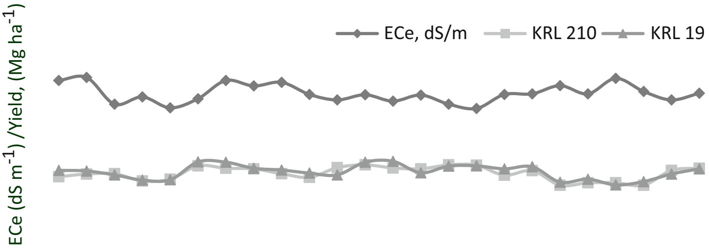
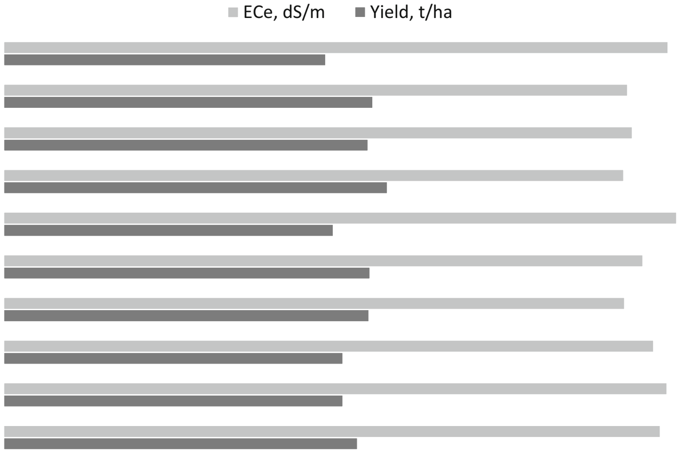


Fig. 22.21 Wheat yield in different clusters taken up by NGOs

in parts of northern India. Farmers' field trials conducted by CSSRI, RRS, Bharuch, in different farm units in collaboration with NGOs like SSKK and GHCL (Saurashtra), MAHITI (Bhal area), VIKAS and ATAAPI (Bara tract) and TCSRD (Jamnagar district) indicated almost consistent yield performance (3.6–3.95 Mg ha^{-1}) of both wheat accessions, KRL 210 and KRL 19, under salinity of 5.9–7.2 dS m^{-1} (Fig. 22.21).

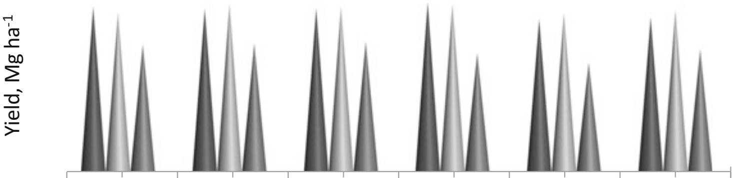
Similarly, in the field trials conducted at Una, Veraval and Jafrabad talukas (coastal areas of Junagadh district), the seed yield is 3.4–3.95 Mg ha^{-1} across all the sites in KRL 210 (Fig. 22.22). Una and Veraval (except for Adri) showed seed yield of about 3.8 t ha^{-1} at salinity ranging from 6.4 to 6.9 dS m^{-1}, whereas at similar salinity, the seed yields reduced by 20 kg ha^{-1} at Jafrabad due to high clay content of the soil. However, the seed yield of the salt-tolerant wheat lines was much higher than the local variety Lok 1 which yielded about 2.5–3.0 Mg ha^{-1} indicating the superiority of salt-tolerant lines and thus their suitability for saline Vertisols of coastal Gujarat (Gururaja Rao et al. 2016; Fig. 22.23). However, significant negative relation was noticed between wheat yield and salinity (Fig. 22.24).

In saline areas of southern, central and Saurashtra areas of Gujarat (EC range 5.9–7.2 dS m^{-1}), salt-tolerant wheat varieties KRL 210 and KRL 19 gave yield in the range of 3.6–3.9 5 Mg ha^{-1}. The increase in number of farmers/user agencies going for the salt-tolerant desi cottons and wheat varieties clearly indicated their impact on the agricultural scenario in the coastal Gujarat (Gururaja Rao et al. 2016).



	Jafrabad			Una			Veraval			
	Balana	Vadhera	Kadiyali	Moto Moli	Kakidi Moli	Vankiya (Sana)	Dari	Vadodara (Dodiya)	Navapara	Adri
■ EC e, dS/m	6.81	6.88	6.74	6.44	6.63	6.98	6.43	6.52	6.47	6.89
■ Yield, t/ha	3.67	3.52	3.52	3.79	3.8	3.42	3.98	3.78	3.83	3.34

Fig. 22.22 Performance of wheat (KRL 210) in coastal saline Vertisols of Gujarat



	SSKK	MAHITI	VIKAS	ATAAPI	TCSRD	GHCL
■ KRL 210	3.86	3.81	3.82	3.96	3.57	3.61
■ KRL 19	3.72	3.92	3.85	3.92	3.71	3.78
■ LOK 1	2.98	3.01	3.05	2.78	2.56	2.87

Fig. 22.23 Comparative performance of CSSRI wheat varieties over local variety (Lok 1) under saline soils of coastal Gujarat

22.7.3 Conjunctive Use of Saline Water with Surface Water for Crop Production on Saline Black Soils

As the real potential of land and water resources in the Bara tract was not assessed, the proper utilization of the land and groundwater resources is of paramount importance in agricultural production. Non-use of saline groundwater is not only making the crop production stagnant but also contributing to the increase in the

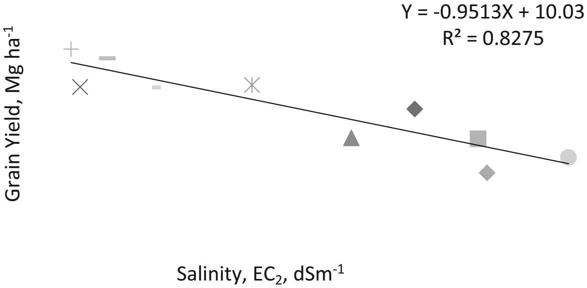


Fig. 22.24 Relation between soil salinity and wheat yield

groundwater table and salinity. The highly saline groundwater in Bhal area in Gujarat renders it not suitable for irrigation as such, and hence it needs to be blended with limited surface water. In the absence of inadequate irrigation water supplies in the region, technologies evolved for conjunctive use of saline groundwater in mixing, and cyclic modes for growing *rabi* season crops like dill, mustard, safflower and wheat proved to be remunerative due to its long-term potential impacts on the economic development, employment generation and environmental improvement (Gururaja Rao 2004).

Dill, a seed spice crop, can be grown during *rabi* season on rainfed saline black soils with salinity of 4–5 dS m^{-1} with a seed yield of 3 Mg ha^{-1}, which otherwise remained fallow. However, the conjunctive use of saline groundwater with surface water can improve the productivity manifold. In dill, if surface water is available for one irrigation, it should be applied at the seed formation stage and saline water at the vegetative and flowering stages. If surface water is available for two irrigations, it should be applied at the time of flowering and seed formation stage and saline water at the vegetative stage. In areas with high groundwater table and lack of sufficient surface water, surface water up to 66% can be saved by application of saline groundwater (4 dS m^{-1}) at branching and flowering stage and surface water at seed formation stage without further increase in soil salinity (Gururaja Rao et al. 2001a; Nayak et al. 1999b, 2001a). This method can increase seed yield by 150% over the yield obtained under unirrigated condition.

In safflower, branching and flowering stages were found to be sensitive stages for saline water irrigation. If surface water is available for one irrigation, it should be applied at branching stage and saline water at vegetation and flowering stages. If surface water is available for two irrigations, it should be applied at branching and flowering stages and saline water at vegetative stage. In safflower by applying saline groundwater (4 dS m^{-1}) at flowering and grain filling stages and surface water at branching stage, 86% increase in yields over the yield obtained under unirrigated conditions (370 kg ha^{-1}) can be obtained (Singh et al. 1996; Nayak et al. 2001a; Gururaja Rao and Khandelwal 2001).

Similarly, Indian mustard (*Brassica juncea*) can be grown on saline black soils with saline groundwater having EC of 4 dS m^{-1} in conjunction with the limited surface water. Flowering and pod formation stages are relatively more sensitive to saline water irrigation. In mustard, application of two saline water irrigations (of

Table 22.20 Effect of conjunctive use of saline water and surface water in cyclic mode on the yield (kg ha^{-1}) of arable crops on saline black soils

Treatments	Dill	Safflower	Mustard	Wheat
T_1 – All BAW	832	825	735	2910
T_2 – SW at branching stage/crown root initiation stage in wheat + rest BAW	793	745	665	2720
T_3 – SW at flowering stage/maximum tillering stage in wheat + rest BAW	784	765	629	2810
T_4 – SW at seed formation stage/ flower initiation stage in wheat + rest BAW	768	775	645	2740
T_5 – SW at branching/tillering and flowering + rest BAW	752	635	559	2220
T_6 – SW at branching/tillering and seed + rest BAW	744	685	519	2300
T_7 – SW at flowering and seed + rest BAW	736	688	535	2230
T_8 – All SW	682	499	326	1680
LSD ($p \leq 0.05$)	06	21	75	500

Source: Gururaja Rao et al. (2001c)
BAW best available water; *SW* saline water

EC_{iw} 4 dS m^{-1}) at branching and pod formation stages and surface water flowering stage resulted in a yield of 559 kg ha^{-1} (Nayak et al. 2001b). Flowering and pod formation stages are relatively sensitive to saline water irrigations. This method while saving 66% surface irrigation water increases the yield by 123% over the yield obtained under unirrigated conditions (220 kg ha^{-1}).

In wheat, good-quality water, if available, should be applied at crown initiation stage and saline water at maximum tillering and flower initiation stages. If surface water for two irrigations is available, it should be applied at crown root initiation and flower initiation stages. Under high saline water table prevailing in saline black soils, in wheat, when saline water is applied, flowering and maximum tillering stages are equally sensitive as that of crown root initiation stage for salinity because of their exposure to increase in groundwater salinity (Gururaja Rao et al. 2001b, 2013d). Application of saline water (4 dS m^{-1}) at these stages and good-quality water at crown root initiation stage resulted in an increase of 180% seed yield when compared to the yield obtained under unirrigated condition (Table 22.20; Gururaja Rao et al. 2000).

The interventions developed for conjunctive use of saline water and groundwater for four important crops of the region would improve dill yield by 446 kg ha^{-1}, mustard by 237 kg ha^{-1}, safflower by 518 kg ha^{-1} and wheat by 1200 kg ha^{-1} over the yield under unirrigated condition. The surface water saved per hectare would create 0.8 ha additional command under irrigation. This technology as well can be extrapolated to other saline Vertisols.

22.7.4 Integration of Medicinal Plants Under Agroforestry System in Saline Vertisols

This is the new paradigm of integration of trees and medicinal plants which can provide an array of products ranging from food, fodder, fruit, fibre, pulp and drugs, etc. for consumption and trade on one hand and conserving the biodiversity and reducing the pressure on the natural resources on the other hand. With dwindling supply from natural resources and increasing global demand, the medicinal plants need to be cultivated to ensure their regular supply. Since majority of the medicinal plants are found in forest and also shade tolerant, therefore, afforestation offers a convenient strategy for promoting their cultivation and conservation (Dagar et al. 2006a, b). Tree-based medicinal system is needed to reduce the pressure on the dwindling resources to obtain sustainable and regular supply of wood, fibre, fruit and medicinal products, to obtain good-quality and genuine raw material for catering the industrial demand, to improve the microclimate by lowering the surface soil temperature, to improve the soil physico-chemical properties, to reduce the soil erosion and finally to increase the farm income.

22.7.5 Cultivation of Biofuel Species on Moderately Saline Vertisols

Biodiesel growth from non-food feedstock is gaining attention around the world. Great emphasis is being given to the production of biodiesel in view of its enormous economic, social and environmental benefits. Biodiesel is a fast-developing alternative fuel in many developed and developing countries of the world. Shortage of edible oil for human consumption in developing countries does not favour its use for biodiesel production. Hence, in India, the focus on tree-borne oilseeds as the source of feedstock for biodiesel production has highlighted the role of *Pongamia pinnata* and *Jatropha curcas*. *Pongamia* is valued for shade, ornamental value, seed oil, fodder and green manure. In recent times, the interest in this tree is mainly focused on the use of its seed oil as biodiesel, which is environmentally safe, nontoxic and biodegradable.

22.7.5.1 *Jatropha curcas*

Jatropha curcas is considered the most suitable biofuel crop since it is cultivated on unproductive lands and degraded forests. Besides, this crop may not replace other important food crops and in turn will not have a major impact on cropping pattern. Studies showed that *Jatropha* grows and performs well in soils having salinity up to 10 dS m^{-1}. Similarly, *Jatropha* plants irrigated with saline groundwater (11.6 dS m^{-1}) on Vertisols with sub-surface salinity also indicated good response in terms of growth, flowering and seed production. Plants irrigated with saline water at three different intervals, i.e. once in 10, 20 and 30 days, indicated that there was no significant difference between 20 and 30 days irrigated plants in terms of growth and seed yield (Sharma et al. 2008, 2010; Singh et al. 2015, Table 22.21). This suggests that marginal quality of saline groundwater can be saved if the crop is irrigated during hot summer once in a month. Though only a marginal decline in seed yield occurred in plants irrigated by saline water at 20 or 30 days, by foregoing this seed yield loss, there can be a saving of marginal saline water by 50–66%. Application of lesser quantities of saline water also reduces salt buildup in the soil.

Table 22.21 Effect of saline water (11.6 dS m^{-1}) irrigation on seed and oil yield of *Jatropha* on saline Vertisols' second year plantation (1111 plants ha^{-1})

Irrigation frequency, days	Irrigation water applied, Litre $plant^{-1}$	Plant height, m	Seed yield, g $plant^{-1}$	Seed yield, kg ha^{-1}	Seed oil content, %	Seed oil yield, kg ha^{-1}
10 (6)	90	1.36	268	2977	35.2	1047.9
20 (3)	45	1.22	184	2044	36.2	739.9
30 (2)	30	1.14	173	1911	36.3	693.7
LSD ($p \leq 0.05$)		0.06	8.54	15.57	NS	10.53

Source: Sharma et al. (2008)

Figures in the parenthesis indicate number of irrigations

22.7.5.2 Intercropping of Dill with *Jatropha curcas*

Salt-affected Vertisols with moderate salinity can also be brought under *Jatropha* cultivation. Experiments conducted indicate response of *Jatropha* to saline water up to 10.4 dS m^{-1}. Since Dill also grows and yields well under saline water, irrigation can be taken up as an intercrop in the initial years since *Jatropha* starts giving economic yield. This approach would provide the farmer returns even during initial years of *Jatropha* cultivation.

22.7.6 Farming System Model to Maximize Productivity on Saline Vertisols

D Esther Shekinah et al. (2005) in their studies on farming systems approach for the small farmer in the rainfed Vertisols of the Western Zone of Tamil Nadu suggested a model comprising (crop + pigeon + goat + buffalo + agroforestry + farm pond) which was the profitable system enterprise that generated higher employment year-round. This system also facilitated the maximum recycling of resources and residues generated on the farm among the enterprises. The output and the waste of one enterprise served as input to another. The nutritive value of the system in terms of carbohydrate, protein and fat was also highest with this enterprise combination. Farming systems with enterprise combination of cropping (fertilized with composted buffalo manure), with pigeon (10 pairs), goat (5:1 female/male), buffaloes (2 milking buffaloes +1 calf), agroforestry and farm pond. The system comprised crop component of maize (F) + cowpea (F) _ chickpea + coriander (0.25 ha), sorghum (F) + cowpea (F) _ chickpea + coriander (0.25 ha), sorghum (G) + cowpea (G) (0.20 ha) and sunflower + coriander (0.10 ha); agroforestry (*Acacia nilotica* + *Cenchrus ciliaris*) (sorghum (F) + cowpea (F) of 0.10 ha; animal component (0.6 ha); and farm pond of 0.4 ha.

Energy budgeting in the farming system suggested that crops like chickpea with high contribution to the output and high milk production from buffalo have resulted in highest energy output of 175,689 MJ $year^{-1}$ from the farming system, indicating the supremacy of the enterprise combination. Manure from the goat enterprise adds

Fig. 22.25 Rainwater harvesting pond (used for irrigation and fish culture), fruit trees (papaya, gooseberry, banana) and *Eucalyptus* tree on dykes (detailed constituents of farming system are given in Table 22.22). (Source: Gururaja Rao et al. 2009)

to the system more energy because crops in farming system are grown with recycled and composted buffalo manure. The energy output of the goat and the buffalo enterprises are low as the energy value of milk and meat is only 4.90 and 4.94 MJ kg^{-1}, respectively, as against 18 MJ kg^{-1} for grains produced. Crop-livestock integration, therefore, increases the overall productivity of ecosystems. Livestock in smallholder farming systems not only increases food production and nutritional supply but also produces residues/wastes that can be recycled and utilized for maximum benefits. Cropping provides an avenue for recycling of animal waste as manure, thereby helping in creating a closed system.

Studies by Gururaja Rao et al. (2009) through farming system studies on saline Vertisols having rainwater harvesting structure (farm pond) and fruit, vegetable, biomass species and field crops (spices) covering an area of 1.12 ha (Fig. 22.25 and Table 22.22) indicated that low water-requiring crops like papaya, dill and coriander had higher water productivity than banana, which is a high water-requiring species.

Data on crop components, crop production, water productivity and benefit/cost ratio (Table 22.23) indicated that spices had higher water productivity (in terms of monetary gains) when compared to vegetables. Vegetables, however, had higher water productivity when yield is taken into account. High water-requiring crops like banana had the lowest water productivity (both in terms of economic yield and monetary gains) and also the benefit/cost ratio when compared to low and moderate water-requiring crops like spices and vegetables. Among the fruit species, papaya was found beneficial both in terms of water productivity and benefit/cost ratio and found suitable for Bara tract. The vegetable crops like tomato, brinjal, bottle gourd and cabbage are moderate in water consumption and are, however, better money

Table 22.22 Components of farming system studied in Vertisol area of Bharuch in Gujarat

Component	Area of each component (m^2)	Crops raised
Pond	2000	
Dykes	900	Banana and papaya fruits and seasonal vegetables
Fruit species	4000	Banana, jamun and gooseberry
Biomass species	3500	*Eucalyptus tereticornis* and *Pongamia pinnata*
Compost pit (m^3)	48	–
Total	11200	

earners due to their continued yielding and thus provide subsistence income to the farmers. The spices, however, because of very low water requirement and high water productivity have been found ideal for water-scarce areas like Bara tract. The B/C ratio of papaya, dill and coriander were higher than banana. Vegetables, brinjal, tomato and bottle gourd had water productivity and also higher B/C ratio than banana. These crops, with low crop duration and low water needs, form ideal components that provide regular income to the farming community. The crops like papaya, dill and coriander along with vegetables because of their higher water productivity and B/C ratio are found to be suitable for the saline Vertisols of Bara tract.

22.7.6.1 Biomass and Fruit Species Under Farming System Model in Saline Vertisols

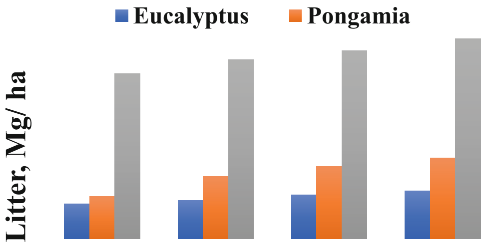
Woody biomass species like *Eucalyptus* and *Pongamia* and fruit crop jamun (*Syzygium cuminii*) were introduced as components of the farming system on saline Vertisols (Gururaja Rao et al. 2009, 2013d), and their contribution to the litter yield was studied. Woody biomass plants such as *Eucalyptus* and *Pongamia* had yielded significant amounts of litter, and their corresponding growth in terms of plant height and girth was also good in the first 4 years after planting. The litter fall was found to be more in *Syzygium* when compared to *Eucalyptus* and *Pongamia*. The compost generated from the litter (Fig. 22.26) of different components was analysed, and the data indicated that it had dry matter of 54.9% and 15% organic matter. The composition of the compost indicated that it is rich in nitrogen and calcium and thus forms a good nutrient source and thus provides a scope for minimizing the use of inorganic fertilizers.

An integrated multi-enterprise model was also developed for sodic soils keeping the requirements of small and marginal farmers (about 2 ha area) in post-reclamation phase comprising diverse components (field and horticultural crops, fishery, cattle, poultry and beekeeping) and has been developed for ensuring sustainable resource use efficiency, high and regular incomes and employment generation. This model was found to reduce the production costs substantially by synergistic recycling of resources among different components (Sharma and Chaudhari 2012; Singh 2009).

Table 22.23 Water productivity and benefit/cost ratio of components in the system

Component	Banana	Papaya	Dill	Corian-der	Brinjal	Tomato	Bottle gourd	Cabbage
Plot area, m^2	190	225	1600	1600	150	160	150	250
Water applied, mm	953	180	120	122	94	104	112	122
Economic yield, kg/plot	887	652	122	116	208	220	324	364
Water productivity, kg m^{-3}	0.931	3.62	1.017	0.951	2.21	2.12	2.89	2.98
Water productivity, ₹ m^{-3}	3.58	19.25	19.85	33.28	15.21	10.00	13.88	17.90
Cost of cultivation, (₹)	1590	1450	960	1120	400	280	490	440
Gross income(₹)	5002	4916	3342	5180	1830	1320	1944	2184
Net income (₹)	3412	3466	2382	4060	1430	1040	1554	1744
B/C ratio	2.15	2.39	2.48	3.63	3.8	3.71	3.17	3.96
Total net income from the system (under yielding stage, ₹ ha^{-1}): ₹ 43,840								

Fig. 22.26 Litter fall in biomass species on saline Vertisols



22.8 Sodic Vertisols: Agro-interventions

The green manuring of dhaincha (*Sesbania aculeata*) along with gypsum is useful practices in restoring of physical condition of sodic soil and enriching the soil in nitrogen and organic matter. Mulching helps in reducing the moisture evaporation from surface soil and prevents salinization. Suitable crop rotation including salt-tolerant crops has also proved successful.

22.8.1 Paddy and Wheat: Ideal Interventions for Sodic Vertisols

Continued trials with paddy and wheat on sodic Vertisols of Madhya Pradesh (Khandkar et al. 2017) indicated that grain yield of paddy and wheat decreased significantly with increase in soil ESP. Incorporation of green manure significantly increased the grain yield over control (Table 22.24). The highest grain yield of paddy and wheat was observed in the application of dhaincha green manure (3.96 and 3.68 Mg ha^{-1}) followed by sunn hemp (*Crotalaria juncea*) (3.57 and 3.50 Mg ha^{-1}) at soil ESP of 25. The lowest grain and straw yield was observed in control plot. The interactions between ESP and FYM/GM (green manure) were also found significant for grain yield of wheat. Further data (Table 22.24) indicated that incorporation of green manures/FYM significantly decreased the ESP at all the levels. The lowest average ESP (22.62) was recorded under incorporation of dhaincha followed by sunn hemp (25.90). However, the pHs and EC$_e$ of soil did not alter significantly.

The data in Table 22.25 showed that the grain and straw yield of paddy and wheat increased significantly due to application of amendments over control. Addition of LS (lagoon sludge) 5 Mg ha^{-1} + RSW (raw spent wash) at 2.5 lakh L ha^{-1} significantly improved grain and straw yield of both the crops compared to gypsum at 75% GR as well as LS at 10 Mg ha^{-1} and press mud (PM) at 5 Mg ha^{-1} application. The highest grain (2.98 and 3.49 Mg ha^{-1}) and straw (6.35 and 4.72 Mg ha^{-1}) yield was noticed under LS 5 Mg ha^{-1} + RSW at 2.5 lakh L ha^{-1} application in respective crops. ESP of postharvest soil was reduced significantly with the application of different amendments. Lowest values of ESP were observed under the application of LS at 5 Mg ha^{-1} + RSW at 2.5 lakh L ha^{-1} after harvest of paddy and wheat.

Table 22.24 Grain yield of paddy and wheat (Mg ha^{-1}) and ESP of the soil after harvest of wheat as influenced by application of green manures/FYM at different ESP levels (Anonymous 2017–2018)

	ESP levels				
Green manures	25 ± 2	35 ± 2	45 ± 2	50 ± 2	Mean
Paddy					
Control	2.79	2.57	1.90	1.35	2.15
FYM at 10 Mg ha^{-1}	3.16	2.81	2.14	1.86	2.49
Sunn hemp	3.57	2.96	2.44	2.03	2.75
Dhaincha	3.96	3.18	2.62	2.35	3.02
Mean	3.37	2.88	2.28	1.90	
	ESP	FYM/GM	ESP × FYM/GM	FYM/GM × ESP	
LSD ($p \leq 0.05$)	0.15	0.15	NS	NS	
Wheat					
Control	2.33	2.04	1.70	1.53	1.90
FYM at 10 Mg ha^{-1}	2.92	2.53	2.15	1.88	2.37
Sunn hemp	3.50	3.06	2.62	2.10	2.82
Dhaincha	3.68	3.29	2.82	2.20	3.00
Mean	3.11	2.73	2.32	1.93	
	ESP	FYM/GM	ESP × FYM/GM	FYM/GM × ESP	
LSD ($p \leq 0.05$)	0.14	0.08	0.19	0.16	
ESP					
Control	22.55	31.05	39.20	43.07	33.97
FYM at 10 Mg ha^{-1}	18.14	25.14	33.42	38.38	28.77
Sunn hemp	17.05	23.03	31.18	32.34	25.90
Dhaincha	14.27	20.72	26.83	28.67	22.62
Mean	18.00	24.98	32.66	35.61	
	ESP	FYM/GM	ESP × FYM/GM	FYM/GM × ESP	
LSD ($p \leq 0.05$)	0.80	0.62	1.33	1.25	

GM green manure

22.9 Summary

Saline and sodic Vertisols, because of their inherent physical constraints like high clay content, low infiltration rate, swelling and shrinking behaviour and low moisture range, pose severe challenges for agricultural crop production. In order to bring such soils under production system, evolving suitable cropping systems with salt-tolerant crops comprising food crops, horticultural crops, forages, woody biomass species and halophytes of high economic value is of paramount importance. This task is very challenging as these soils provide many constraints even at low salinity. Agroforestry-based farming systems involving fruit trees, milk cattle, low water-

Table 22.25 Yield (Mg ha^{-1}) of paddy and wheat and ESP after harvest of crop as influenced by different treatments (Anonymous 2014–2015)

	Paddy		Wheat		ESP	
Treatments	Grain yield	Straw yield	Grain yield	Straw yield	Paddy	Wheat
Control	1.40	2.97	1.99	2.69	36.4	36.1
GR at 75%	2.33	4.95	3.08	4.14	22.0	21.2
RSW at 5 lakh L ha^{-1}	2.60	5.52	3.35	4.50	19.1	18.6
LS at 10 Mg ha^{-1}	2.22	4.71	2.86	3.84	23.0	22.5
PM at 5 Mg ha^{-1}	2.14	4.57	2.70	3.63	25.9	25.5
LS at Mg ha^{-1} + RSW at 2.5 lakh L ha^{-1}	2.98	6.35	3.49	4.72	16.5	16.1
PM at 2.5 Mg ha^{-1} + RSW at 2.5 lakh L ha^{-1}	2.46	5.29	3.27	4.45	20.2	19.9
SEm ±	0.05	0.09	0.06	0.08	0.49	0.42
LSD ($p \leq 0.05$)	0.14	0.26	0.17	0.24	1.46	1.23

GR gypsum requirement, *RSW* raw spent wash, *LS* lagoon sludge, *PM* press mud

requiring stress-tolerant crops and medicinal and aromatic crops have been found as ideal option for these soils. Silvo-pastoral system has been advocated as a promising sustainable option for saline and sodic conditions. *Salvadora persica* has been proved quite remunerative even on highly saline Vertisols with salinity up to 35–40 dS m^{-1}. While aromatic herb, *Anethum graveolens*, proved to be beneficial on moderately saline Vertisols, the use of medicinal plants along with woody tree species for saline soils has also been suggested. Among other halophytes, *Salicornia* and *Arthrocnemum* have been found ideal for saline Vertisols. Sodic Vertisols, with suitable amendments, can be brought under cereal production system. While giving importance for diverse crop interventions, land configuration methods can also be planned for sodic Vertisols.

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Saline Agroforestry: A Hanging Fruit for Saline Waterlogged Ecologies

23

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Abstract

There are different sources of salt accumulation in the soil. The factors responsible for waterlogging in salt-affected soils include heavy rainfall and runoff accumulation, insufficient provision for drainage, faulty practices for management of irrigation water, shallow water table, unlined irrigation system, seepage from the upstream reservoirs and flat to concave land topography. These problems of waterlogging and soil salinity are common world over which have significantly reduced the productivity of lands. The engineering-based reclamation measures are effective for controlling these problems, but their large-scale adoption is constrained due to high investment, annual maintenance cost and problems due to disposal of harmful drainage effluents. Tree plantations have shown lot of potential to control salt-affected waterlogged situations. Different tree species are suitable for enhancing productivity and improvement of such sites by reducing salinity and lowering water table through biodrainage of excess water. Various factors such as type of tree species, tree spacing and method of planting should be considered while designing agroforestry measures for such sites. Tree species selected should develop a full canopy as quickly as possible and have deep roots and tolerance to salinity and waterlogging. Ridge-trench method is the best suited method for planting of trees in saline waterlogged soils. Different tree species have been found suitable for controlling salinity and waterlogging in various regions of the world. In Kenya, *Balanites aegyptiaca* was the most effective agroforestry tree species in the form of parkland where salinity problems were prominent. Some recommended species for wastewater irrigation in Egypt include *Eucalyptus* spp., *Pinus* spp., *Populus* spp. and *Khaya ivorensis*. In North America, six halophytes (*Atriplex lentiformis*, *Salicornia bigelovii*, *Spartina gracilis*, *Distichlis spicata*, *Bassia hyssopifolia* and

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Allenrolfea occidentalis) and some salt-tolerant forage species have been suggested for saline-sodic and waterlogged sites. In the USA, *Atriplex* plantations grown with high salinity water are highly productive. In Pakistan, *Eucalyptus camaldulensis* was the most appropriate species along with some other local tree species such as *Acacia nilotica*, *Tamarix articulata* and *A. modesta*. *Elaeagnus angustifolia* with more transpiration rate, tolerance to salinity and good growth was observed as the most potential tree in Uzbekistan. In Iraq, *Tamarix* plantations have been found most effective. In India, *Eucalyptus* and bamboo have been found as excellent biodrainers which could control the salinity and waterlogging problems of irrigated agriculture. Some other tree species selected for land reclamation and biodrainage in India are *Terminalia arjuna*, *Casuarina glauca*, *Syzygium cuminii*, *Pongamia pinnata*, *Acacia nilotica*, *Tamarix troupii* and *Prosopis juliflora*. In China, the tree species selected for land reclamation are *Acacia nilotica*, *Prosopis juliflora*, *Tamarix troupii* and various bamboo (*Bambusa*) and *Eucalyptus* species. *Eucalyptus camaldulensis* is being preferred for improvement of salt-affected soils in Australia. Some most useful pasture species for salt-affected soils in Australia include *Thinopyrum ponticum*, *Puccinellia ciliata*, *Atriplex undulata* and *Atriplex lentiformis*. In Europe, important species are willow (*Salix*), ash (*Fraxinus*), silverberry (*Eleagnus*), poplar (*Populus*) and black locust (*Robinia*). Major benefits accruing due to adoption of agroforestry on salt-affected waterlogged soils are being discussed. The growing of different tree species leads to timber production, fuelwood, fodder and other tree-based products and enhances the income of the farmers adopting agroforestry-based technologies. Biodrainage potential of tree species leads to lowering of water table and reduction in soil salinity. The planned plantation can help achieve optimum water as well as salt balance in saline waterlogged lands through biodrainage. The restoration of degraded salt-affected waterlogged soils under tree cover is also attributed to gradual improvements in their properties. These effects contribute to the productivity enhancement of salt-affected soils. However, saline agroforestry is still a hanging fruit, and its maximum potential can be extracted by adoption of saline agroforestry practices on a landscape scale in saline waterlogged areas.

Keywords

Biodrainage · Halophytes · Saline agroforestry · Salt-affected soils · Subsurface drainage · Waterlogging

23.1 Introduction

Salinity is caused due to an imbalance between inputs and outputs of water in a catchment. The water table rises bringing salts to the surface when more water enters into the catchment than going out. When water evaporates from shallow water table, salts can accumulate at the soil surface. There are different sources of salts accumulating in the soil. Excess salts may accumulate in the surface horizons of soils mainly due to secondary salinization associated with waterlogging, high salt content of irrigation water, release of immobilized salts already precipitated in soils, salt depositions from atmosphere and release from soil minerals and fertilizers. The relative significance of each source in contributing salts in the soil depends on the natural drainage conditions, soil properties, irrigation water quality, management practices and distance from the coast line. Soluble salts are either neutral in their reaction (e.g. sulphates and chlorides of Na, Ca and Mg) or are the alkali salts (bicarbonates and carbonate of Na) capable of producing alkalinity.

Salt-affected soils vary from normal soils mainly with respect to soil reaction and amounts of soluble salts. Higher quantity of soluble salts adversely affects the soil behaviour by changing physicochemical properties of soil. These properties have a great effect on the activity of plant roots as well as growth of the plants. These soils occur extensively in different agroecological regions of the country particularly the dry subhumid, semi arid and arid regions. With the increasing demand for good-quality water and land for urbanization, agriculture would be pushed to such marginal areas.

Salinity is one of the important factors that influence germination of halophytes (Heard and Ancheta 2011). In addition, waterlogging influences yield of crops in low-lying areas. Lower oxygen level in waterlogged soils adversely affects water and nutrient uptake by shifting energy metabolism from aerobic to anaerobic mode. Plants suitable for growing under waterlogged situations can cope with this stress in the form of aerenchyma formation, higher activity of glycolytic pathway and higher availability of soluble sugars.

Many technologies have been developed for amelioration of salt-affected waterlogged sites in various regions of the world. These include management of such sites through engineering measures and various agroforestry practices involving tree species, shrubs and grasses. Engineering approaches do not have large-scale adoption due to high capital investment and annual maintenance cost. Agroforestry measures have lot of potential to ameliorate such sites and make them productive by reducing salinity and waterlogging through biodrainage of excess water and improvement of soil properties.

23.2 Salt-affected Soils

Salt-affected soils are categorized on the basis of nature of soluble salts present and management practices needed for their reclamation. Salts are either neutral or alkaline in nature, and therefore salty soils are grouped into saline and alkali soils.

In saline soils, white crust of salts is formed on the soil surface. Soluble salts are usually determined by measuring electrical conductance (EC) and are invariably present in large quantities. Salts are mainly the sulphates and chlorides of Na, Ca and Mg. Electrical conductance of the paste extract (ECe) is higher than 4 dS m^{-1}, and pH of soil paste is less than 8.2. Sodium adsorption ratio (SAR) which is a measure of soil sodicity may be less or more than 15. In alkali soils, pH of the soil paste is greater than 8.2. The soils have exchangeable sodium percentage (ESP) or SAR more than 15 and have soda type salts (carbonates and bicarbonates of sodium). Salt encrustation with black colour appears near organic carbon spots. Water stagnates and does not infiltrate in the soil for long periods, and a layer of calcium carbonate concretions is normally found in the subsoil (1–1.5 m depth).

Salt-affected soils are mainly found in semi arid and arid areas of the country. Rainfall is generally less than 700 mm in most of these areas, and about 80% of the rainfall is received during monsoon season. In the post-monsoon season, water need of the transplanted saplings is met either through groundwater or through canal water. The presence of poor quality underground water makes the problem more complex. It has been observed that groundwater underneath most saline soils has excess of salt load or high SAR.

23.2.1 Salt-affected Waterlogged Soils

A large number of factors are responsible for waterlogging in the salt-affected soils. These include heavy rainfall and runoff accumulation, clayey soil, inadequate drainage, faulty practices for irrigation water management, shallow water table, unlined irrigation systems, seepage from the upstream reservoirs and flat to concave land topography. The problems of soil salinity and waterlogging are common world over. About one-third of irrigated area in the world (255 million ha) has threat of waterlogging, about 60 million ha is waterlogged, and 20 million ha is salt-affected (Heuperman et al. 2002). Introduction of large-scale canal irrigation system has led to salinity and waterlogging problems (Kumar 2004). There is variable information in the estimation of saline and waterlogged areas in India. The area under salt-affected soils is approximately 6.73 million ha, and waterlogged area is 6.41 million ha (Anonymous 2010). Another estimate showed that about 4.53 million ha by waterlogging and 8.56 million ha by soil salinity are afflicted (Tanwar 1997). Many Indian states such as Maharashtra, Gujarat, Orissa, Uttar Pradesh, Punjab, West Bengal, Bihar, Andhra Pradesh, Tamil Nadu, Haryana, Rajasthan and Kerala are facing problems of salinity and waterlogging. These problems are also common in arid and semi arid regions of the world (Mohamedin et al. 2010). Excessive use of groundwater has caused seawater intrusion and salinity problem in many coastal areas. Salinization and waterlogging have led to decrease in productivity of lands on a large tract (Dwivedi 2006). High concentrations of salts in soil can result in adverse physical, chemical and biological characteristics resulting in poor soil structure, fertility and physiological drought conditions (Dash et al. 2005; Sarangi and Bundela 2011). Excessive soil salinity or irrigation water salinity decreases the capacity of plant to extract water and nutrients, which ultimately affects the production of crops (Fig. 23.1).

In many canal-irrigated arid and semi arid areas of the country, waterlogging and subsequent secondary salinization have turned vast stretches of agricultural lands unproductive. Water seepage from canals and faulty on-farm water management practices together create shallow water table conditions and significant increase in

Fig. 23.1 Mustard field in Muktsar district (Punjab, India) with patches of salts deposited on surface

root-zone salinity due to higher capillary salinization (Chhabra and Thakur 1998). The twin problems of excessive salt accumulation and waterlogging, often collectively referred to as secondary salinity or irrigation-induced salinity, have emerged as major obstacles in sustainable and profitable crop production in many irrigated commands of India, and the problem has become particularly alarming in northwestern states. In most of the cases, poor irrigation water management and clearing of perennial vegetation (Turner and Ward 2002) induce severe salinity build-up in arable lands. Waterlogging, salinity and alkalinity problems have arisen in southwestern districts of Punjab. The water table in such areas rose at the rate of 15–20 cm per annum due to canal irrigation network and insufficient drainage system (Shakya et al. 1995). According to an estimate, about 85,000 ha of arable land in 332 villages of Faridkot and Muktsar districts are severely affected by waterlogging and salinity (Anonymous 2009). The groundwater contains high concentration of dissolved salts with EC varying from 2 to 7 dS m^{-1} and residual sodium carbonate (RSC) being more than 10 me l^{-1} up to 10 m depth (Shakya et al. 1995). In general, groundwater salinity of this area increases with depth, and the water is not fit for irrigation and drinking purposes. In the near future, the secondary salinity can create severe environmental impacts by altering the geohydrological features to the extent that rapid mobilization of primary and fossil salts stored in lower soil profiles would even cause the problem of river salinization (Smedema and Shiati 2002).

23.3 Management Through Surface and Subsurface Drainage

The problems of salinity and waterlogging can be controlled by engineering measures such as surface and subsurface horizontal or vertical drainage with proper design and installation. But their large-scale adoption on farmers' fields is constrained by high investment, annual maintenance cost and problems of harmful drainage effluents disposal leading to environmental degradation. The limitations of the drainage techniques thus call for other alternative methods for sustainable agriculture. These methods should be affordable, efficient, environment-friendly and acceptable to the society.

The usefulness of subsurface drainage as an effective technological intervention to overcome the problems of salinity and waterlogging is well known (Gupta 2002). The subsurface drainage network consists of concrete or PVC pipes along with filters installed at a particular depth and works by draining out the excess water containing soluble salts. A large tract of waterlogged saline soils has been reclaimed by this method and put under crop production. The crops grown in the reclaimed saline soils exhibit high to very high increase in yield (45% in paddy, 111% in wheat and 215% in cotton) and cropping intensity (Sharma et al. 2014). In spite of tangible socio-economic benefits in terms of on farm employment generation and productivity gains, the rapid adoption of this technology is hindered by the higher initial establishment costs, operational difficulties, lack of community participation and the problems encountered in disposal of drainage effluents. Although farmers are fully aware of the benefits of subsurface drainage, they could hardly afford the higher costs involved in establishment and maintenance of these systems. In most of the salinity affected regions of the country, water users' organizations for irrigation and drainage projects are almost non-existent. Since the success of subsurface drainage projects rests on collective responsibility, appropriate institutional arrangements for farmers' participation and organization are required (Ritzema et al. 2008).

23.4 Agroforestry to Combat Salinization and Waterlogging

The engineering approaches for managing waterlogged saline soils cannot be afforded by poor farmers in developing countries. The plantations of trees have shown a lot of possibility to manage waterlogged conditions all over the world. The operational difficulties of engineering technologies have generated interest in other viable alternatives such as biodrainage for harnessing the productivity of waterlogged sites (Ram et al. 2011). Biodrainage refers to the bioenergy-driven pumping of excess soil water and dissolved salts through rapid transpiration by the perennial trees (Heuperman et al. 2002). Analogous to energy-operated water pumps, it is a proven technology to prevent salinity build-up in canal command areas when appropriate tree species are grown at the right time to prevent waterlogging and salinization.

Agroforestry has emerged as an effective technology for improvement of salt-affected soils and waterlogging especially in canal command areas in different countries. In addition to reclamation of salt-affected soils in arid and semi arid regions, productivity of coastal areas can also be increased by adopting agroforestry measures (Dagar et al. 2014). The productivity can be increased by adopting integrated farming systems having tree plantations, crops, fruit trees, animals and aquaculture. Mangroves are helpful in protecting seashore, sustaining the livelihood security of coastal people and for protecting wildlife. Different halophyte species can meet the various demands of people such as food, fodder, oil, aromatic and medicines. Highly productive salt-tolerant genotypes should be developed for greater benefits. Different factors such as the tree species, their spacing and location in the catchment and method of planting should be considered while designing agroforestry systems for controlling salinity and waterlogging.

23.4.1 Spacing of Trees

Trees have higher capacity than crops and pastures to reduce recharge by using the water stored in the soil. However, the rate of water uptake by trees will depend on their leaf area. Tree spacing will influence the leaf area, and therefore leaf area of trees would be more in case of closer than wider spacing. Therefore, tree density should be selected in a way that produces higher leaf area in a shorter time. On the other hand, leaf area of widely spaced trees can ‘catch up’ to closely spaced trees after a few years because the final leaf area achieved is controlled by climate, soil and performance of species than spacing only. Therefore, the factors such as selection of tree species and their benefits, access, weed management, etc. should also be considered while selecting tree spacing. The rate of transpiration from trees is generally higher on the plot borders than that in the middle. Thus, effectiveness of tree planting will be more if these are planted in small clumps or strips than in larger blocks.

23.4.2 Location of Trees

The recharge of groundwater would be in all parts of the catchment. However, recharge will vary on different sites, and it will be very fast on some sites. For an example, it would be very fast on light-textured soils or on broken rocks where water enters very quickly and moves downwards. Trees should be planted mainly on such sites for their greatest effect on recharge and salinity. It should be strictly taken care that identified recharge area is related to the saline area being controlled. Local knowledge of hydrogeology is important for an effective exercise.

23.4.3 Selection of Species

Trees will decrease recharge of water by transpiring water stored in the soil. Deep-rooted species should be preferred over shallow-rooted species. These species will be able to take and transpire water from deeper layers of soil. The tree species tolerant to waterlogged and salt-affected conditions should be planted because these will establish and grow better on such problematic sites and contribute more towards groundwater discharge and reduction of salinity than species sensitive to such conditions. Forestry departments and local nurseries should give advice to farmers regarding suitability of species for different areas. Soil and climatic conditions are important to consider before planting these species. The chances of survival and better growth performance are more in case of local tree species. Therefore, time and money should not be wasted for establishing tree species that will not perform well in the problematic area.

Fig. 23.2 Planting of *Eucalyptus* by ridge-trench method on saline waterlogged soils without and with polythene sheet. (Courtesy: Dr. Avtar Singh, RRS Bathinda, PAU, Ludhiana)

23.4.4 Method of Planting

Planting on the ridges is a normal practice for low-lying areas where water can stagnate in the pits. Ridge-trench method is best suited for salt-affected waterlogged soils, and no other method has been found suitable for such soils. In this system, seedlings are established in the centre of the ridges or near the borders of the wider ridges in case of double-row planting. Ridges in saline soils increase the chances of salt accumulation on surface when water evaporates leaving the salts behind. Therefore, application of plastic sheets may help in checking the movement of salts. Therefore, the growth in rows covered by plastic sheets was found better as compared to without plastic cover (Fig. 23.2). The stability of ridges reduces due to salt accumulation on surface and edges of the ridges. Also, repair of ridges and need of spot irrigation increases the cost factor for maintaining plantations.

23.5 Agroforestry Technologies Developed in Different Countries

23.5.1 Africa

In north-western Kenyan zone rangelands, the survival of indigenous species is higher than the exotic species. Exotic species being prone to water and saline stress exhibited higher mortality, and hence the indigenous species were promoted for cultivation. *Balanites aegyptiaca*, a promising agroforestry tree in parklands (arid and semi arid areas), fulfils the requirement of adequate germination, growth and its ability to reduce concentration of salts in soil (Hall 1992). *Eucalyptus*, an exotic species, has dual rooting system, viz. shallow roots just beneath the soil and tap roots which can penetrate deep up to the water table. Horizontally extending shallow roots (3–5 m) absorb surface soil moisture. The tap roots extend vertically (up to 9 m) and reach permanent groundwater aquifers. These roots help *Eucalyptus* tide over water stress during dry periods, and the tree survives with adequate growth in Ethiopia (Fritzsche et al. 2006).

In Egypt, due to persistent waterlogging, soil salinization is a major problem (Mohamedin et al. 2010). The waste water generated by the villages and cities is used for irrigating forest plantations. Pine (*Pinus* spp.), eucalyptus (*Eucalyptus* spp.), poplar (*Populus* spp.) and beech wood (*Gmelina arborea*) used for pulpwood/ sawnwood and mahogany (*Khaya ivorensis*) and teak (*Tectona grandis*) for high-value products have been recommended for cultivation in waste water irrigated areas based on their suitability, growth potential and economic value (Zalesny et al. 2011).

23.5.2 North America

Prolonged waterlogging leads to gradual build-up of salts in soils in the USA. Tree plantations with ability to biodrain help rehabilitate the salt-affected soils. The efficiency of tree species in soil salinity reduction is constrained by the increasing presence of toxic salts in groundwater. In California, *Eucalyptus* is used extensively as it can transpire actively in saline conditions (groundwater salinity is ~ 8 dS m^{-1}). Saline water can be used for long-term irrigation of halophytic species (*Salicornia bigelovii*, *Atriplex lentiformis*, *Spartina gracilis*, *Allenrolfea occidentalis* and *Bassia hyssopifolia*). These species adopt to high saline-sodic soil conditions (ECe 28.6 dS m^{-1}) and produce average standing biomass (dry matter) ranging from 3.8 to 17.4 Mg ha^{-1} (Diaz et al. 2003). Salt withstanding forages like alfalfa (*Medicago sativa*), narrow leaf trefoil (*Lotus glabra*), tall wheatgrass (*Agropyron elongatum*), alkali sacaton (*Sporobolus airoides*), paspalum grass (*Paspalum vaginatum*) and Bermuda grass (*Cynodon dactylon*) can also be cultivated. In the USA, *Atriplex* yields 12–20 Mg ha^{-1} dry matter when raised using saline water (Watson 1987; Aronson 1989). For sustainable and productive tree plantations, adoption of conventional surface and subsurface technology is needed. Availability of good-quality irrigation water and/or its use in conjunction with conventional drains is essential for cultivation of plantations in arid and semi arid regions as demonstrated in Quebec, Canada.

23.5.3 Asia

Agroforestry systems have proved one of the best land use options economically and ecologically in many areas of South Asia (Kaur et al. 2002). Kushiev et al. (2005) identified the potential of *Glycyrrhiza glabra* cultivation for reclamation of saline areas in the Hungry Steppes of Central Asia where higher water tables were due to inadequate drainage infrastructure and poor management of irrigation water. Salinity problems have adversely affected the production potential of Iraq rendering 30% of its irrigated area completely out of production. In southern Iraq where salinity levels are extremely high and installation of drainage systems is practically not feasible or very costly, reclamation through cultivation of various salt-tolerant species could be a useful alternative. Many scientists have reported tree species that can be used effectively under such circumstances (Djavanshir et al. 1996; Guiti 1996). *Atriplex* and *Tamarix* plantations were found as effective tree species in reducing the salinity of top soil. The cultivation of *Petropyrum euphratica*, *Haloxylon persicum*, *Haloxylon aphyllum* and *Tamarix aphylla* was also recommended based on different experiments.

In Pakistan, approximately 4.5 million ha area has been affected by salinity (Qureshi 2011). Inappropriate management practices, poor quality irrigation water as well as faulty drainage systems are the main causes for waterlogging and salinity in India and Pakistan. In Bangladesh, intrusion of seawater has resulted in salinity of about 1 million ha of coastal zone of the Ganges-Brahmaputra River Delta (Hossain 2010). For such circumstances, agroforestry and forestry systems could be a viable alternative (Wicke et al. 2013). Wetlands areas as in Bangladesh can successfully be utilized for agroforestry (Ghosal et al. 2004). Tolerance potential of *A. nilotica* and *A. ampliceps* against salinity and water shortage was evaluated in pots (Abbas et al. 2016). Three-month-old plants of both these species were transplanted in the pots with various salinity levels (10, 20, 30 dS m^{-1} and control). After 2 weeks, water stress was applied continuously till the end of the experiment. After 4 months, data regarding ionic composition (Na^+, K^+ and Cl^-) of shoot and root was determined by wet digestion. The results demonstrated that *A. ampliceps* was more tolerant to salinity due to better ionic composition and physiological attributes, but when salinity was associated with water stress, its tolerance potential declined. Whereas, *A. nilotica* performed better under water stress and when salinity was associated with water stress (Abbas et al. 2016). Many salt-tolerant species have been recognized in Pakistan (Singh 1989; Aslam et al. 1993), which include highly salt-tolerant tree species (*Prosopis chilensis*, *P. juliflora*, *P. alba*, *Acacia ampliceps*, *Tamarix articulata*, *Salvadora persica*) or moderately salt-tolerant species (*Acacia tortilis*, *A. nilotica*, *A. cambagei*, *Casuarina equisetifolia*, *Eucalyptus tereticornis*, *E. camaldulensis*, *E. microtheca* and *Azadirachta indica*). Zafar (1990) reported that *E. camaldulensis* was most useful species for waterlogged saline soils, while Altaf-Hussain (1991), Sahibjada (1993) and Marcar and Crawford (1996) advocated indigenous trees such as *Acacia nilotica*, *A. modesta* and *Tamarix articulata* and some exotics like *Atriplex stenophylla*, *A. ampliceps* and *Casuarina* for waterlogged and saline conditions in Pakistan.

Dash et al. (2005) evaluated the biodrainage potential of various tree species in relation to their growing stage, growth rate, density of plants and other edaphic and climatic conditions. Khamzina et al. (2005, 2006) assessed the potential of nine multipurpose tree species like *Populus nigra* var. pyramidalis, *Prunus armeniaca*, *Salix nigra*, *Catalpa bignonioides*, *Fraxinus pennsylvanica*, *Elaeagnus angustifolia*, *Morus alba*, *Ulmus pumila* and *Populus euphratica* for their suitability for biodrainage in declining the raised groundwater table through the transpirative capacity of tree plantations in degraded land of the Khorezm region, Uzbekistan. *Elaeagnus angustifolia* with fast growth, high transpiration, salinity tolerance and production of nutritious feed had maximum potential. Growth of *Ulmus pumila* and *Populus* sp. was less consistent but sufficient enough to make them potentially suitable candidates. Saline soils down to 0.45 m depth have been successfully reclaimed by cultivating kallar grass (*Leptochloa fusca*) till 5 years; afterwards the field can be put to grow normal crops. The perennial forage grasses like tall wheatgrass (*Elytrigia elongata*) and Rhoades grass (*Chloris gayana*) have shown potential to salt tolerance. Qureshi and Akhtar (2002) reported that saltbushes such as river saltbush (*Atriplex amnicola*) are highly salt-tolerant forage bushes.

Chhabra and Thakur (1998) of CSSRI, Karnal, India, conducted a lysimeter experiment to assess the capacity of biodrainage to control soil salinity and waterlogging. *Eucalyptus* and bamboo were selected as the test plant species. The study revealed that a *Eucalyptus* tree could remove 280–550 cm of water per year during different years of its growth, while a bamboo tree could drain approximately 130–320 cm of water. Thus these tree species were excellent biodrainers which could control the salinity and waterlogging problems of irrigated agriculture because of high-transpiration rate and a capacity to pull out water from lower soil profile. Dagar et al. (2016) observed the effect of *Eucalyptus tereticornis*-based agroforestry system comprising rice and wheat crops on reclamation of saline waterlogged soils. The rate of transpiration of *Eucalyptus* on an average was 68.0, 71.5 and 73.8 L per day per tree in 1 m × 1 m, 1 m × 2 m and 1 m × 3 m tree spacing, respectively, in strip plantation as compared with 40.0 L per day per tree in block plantation. Similarly, the total amount of water transpired per annum was 745 mm in 1 m × 1 m, 391 mm in 1 m × 2 m, 269 mm in 1 m × 3 m tree spacing and 1825 mm in block plantation. High transpiration rate of *Eucalyptus* resulted in lowering of water table by 43.0, 38.5 and 31.5 cm in 1 m × 1 m, 1 m × 2 m and 1 m × 3 m spacing, respectively, during the fourth year of plantation than in nearby fields without plantation. Sarkar et al. (2018) investigated the soil moisture and groundwater dynamics underneath four biodrainage vegetations, viz. kadamba (*Neolamarckia cadamba*), eucalyptus (*Eucalyptus* sp.), lamboo (*Dysoxylum* sp.) and banana (*Musa* sp.) in waterlogged lands of Indo-Gangetic plain of West Bengal, India. The results showed that tree canopy of *Eucalyptus* had higher efficiency in exhausting the surplus water from deeper soil layers and lowering the uprising groundwater table than underneath bamboo, banana and kadamba plantation.

Due to salt stress, plant growth may be hampered by the osmotic effects on water uptake and disruption in ion homeostasis within the cells that may damage membranes and inhibit plant metabolism. Under such conditions, plants require extra energy to adapt to the harsh environment and lower the risk of salt injury (Tester 2003; Tripler et al. 2007, 2011). In China, different plant species selected for land reclamation are *Tamarix troupii*, *Acacia tortilis*, *Acacia nilotica*, *Prosopis juliflora* and different bamboo and *Eucalyptus* species (Zhao et al. 2004). Zhang et al. (2015) evaluated the performance of two halophytes, *Haloxylon ammodendron* and *Suaeda physophora*, and a xerophyte, *Haloxylon persicum*, under saline-waterlogging and dry-moist cycles. The results indicated that aeration improves germination of all species when NaCl was applied to seeds, particularly for xerophyte. As compared to *H. ammodendron* and *S. physophora*, recovery germination, seed germination, and total germination of *H. persicum* were much lower when seeds were soaked in 700 mM NaCl. However, the germination parameters of non-germinated seeds increased drastically for *H. persicum*, when these were submerged in 700 mM NaCl with aeration. Thus, seeds of the two halophytes performed better under waterlogging and dry-moist cycles than seeds of the xerophyte. In China, halophytes that are cultivated in agroforestry systems in saline soils are utilized as source of oil (*Suaeda*, *Salicornia*), starch and protein (species of *Atriplex*, *Zostera*, *Chenopodium*), food and therapeutic value (*Limonium bicolor*), medicine (*Lycium barbarum*, *Ephedra sinica*, *Xanthium sibiricum, Glycyrrhiza uralensis*, *Kochia scoparia*, *Artemisia stelleriana*), fibre (*Apocynum venetum*) and fodder for domestic animals (*Pennisetum alopecuroides*, *Spartina anglica*, *Agropyron sibiricum*, *A. mongolicum*, *Elaeagnus angustifolia*, *E. umbellate*, *Nitraria sihirwa*) (Kefu et al. 2011).

23.5.4 Australia

In Australia 32 million ha land is salt-affected, and majority of it is subject to primary salinity. About 5.7 million ha land is at high risk of secondary salinity, and 17 million ha is expected to be at high risk by 2050 (Barrett-Lennard 2003). It was concluded that waterlogging under saline conditions increased leaf senescence and inhibited the ability of the roots to exclude salts, so that the concentrations of chloride and/or sodium substantially increased in the leaves or shoots of all the 24 plant species tested except rice. Pastures are attractive alternative of obtaining production and rehabilitation of waterlogged salt-affected soils. These pastures comprise salt-tolerant forage shrubs (species of *Halosarcia*, *Atriplex* and *Maireana*), perennial grasses (*Thinopyrum ponticum*, *Puccinellia ciliata*, *Paspalum vaginatum*, *Distichlis spicata*, *Pennisetum clandestinum*, *Sporobolus virginicus*, *Chloris gayana*, etc.) and some annual species. Barrett-Lennard (2003) showed relative ranking of different salt-land pasture species and indicator species in the salinity/waterlogging matrix. Some of the most successful species for Australian salt-affected lands have been introduced from other countries and performed well, and those include *Distichlis spicata* from the USA, *Atriplex undulata* (wavy leaf saltbush), *Atriplex lentiformis* (quail bush) from Argentina and *Puccinellia ciliata* and *Thinopyrum ponticum* (tall wheatgrass) from Turkey. In a comparative performance of ten perennial grass species at five salt-land sites across southern Australia, Nichols et al. (2008) concluded that *Puccinellia* was the best performing species. It was hypothesized that the variability in zonation of *Puccinellia* and tall wheatgrass is primarily caused by variations in the tolerance of these two species to waterlogging under saline conditions (Jenkins et al. 2010). *Puccinellia* and tall wheatgrass showed similar growth responses to salinity under well-drained conditions, with 50% lower shoot dry mass (DM) at about 300 mM NaCl. However, the integration of salinity (250 mM NaCl) and waterlogging increased the shoot DM of *Puccinellia* by 150% but decreased tall wheatgrass shoot DM by 90% as compared with salinity alone.

Sun and Dickinson (1995) reported that there was no major difference in survival between *E. camaldulensis* and *Casuarina cunninghamiana* when grown on a salt-affected site in dry tropical Australia. However, these had typically different root systems, with that of *E. camaldulensis* being more efficient in lowering the groundwater table. Because of this, growth of *E. camaldulensis* was faster than *C. cunninghamiana* at both moderate and low salinity levels. Hence *E. camaldulensis* was more suitable for reclamation of salt-affected land under moderate or low salinity conditions. Turner and Ward (2002) advocated that a combined belts of perennial pasture and trees, such as lucerne (*Medicago sativa*) and saltbush (*Atriplex* spp.), could diminish and even revert waterlogging and secondary salinity while maintaining crop productivity at moderate level. Saline drainage water with salt concentration of 10 dS m^{-1} or more would significantly reduce the growth and water use of pulpwood species such as *Eucalyptus globulus*, *E. grandis* and *E. camaldulensis*, particularly on heavy soils. High salt-tolerant but low productive species such as *E. microtheca*, *E. occidentalis* and *Casuarina glauca* could be grown successfully.

For southwest area of Western Australia degraded through waterlogging and secondary salinity, Angell et al. (1994) advocated some suitable salt-tolerant pasture and trees species. For mildly saline (EC 5–10 dS m^{-1}) regions, pastures consisting of *Chloris gayana*, *Phalaris* sp., *Secale cereale*, *Thinopyrum ponticum*, *Trifolium michelianum* and *T. resupinatum*; for moderate salinity (EC 10–15 dS m^{-1}), trees such as *Eucalyptus sargentii*, *E. occidentalis*, *E. loxophleba*, *E. spathulata*, *E. camaldulensis*, *Acacia saligna* and *Casuarina cunninghamiana* associated with pasture grasses such as *Puccinellia ciliata* (Puccinellia), *Thinopyrum ponticum* (tall wheatgrass), *Chloris gayana* (Rhodes grass) and *Phalaris* spp.; and, for highly saline region (EC 15–20 dS m^{-1}), trees such as *Casuarina obesa* and *Melaleuca cuticularis* with pasture grasses like *Puccinellia* may be planted successfully with trees such as *E. rudis*, *E. camaldulensis*, *E. robusta*, *E. melliodora* and *E. microcarpa*. Furthermore, stabilization of salt-affected land and its productive use with the use of saltbush and strategically placed trees has also been advised (Marcar et al. 2003). Commercially grown eucalypts, like *E. grandis* and *E. globulus*, are slightly salt-tolerant. On the contrary, few species with less commercial potential, viz. *E. occidentalis*, *E. sargentii*, *Acacia stenophylla* and *E. spathulata*, are highly salt-tolerant, with less growth reduction at ECe 10 dS m^{-1} (Marcar et al. 2003; Zohar et al. 2010).

23.5.5 Europe

The indigenous trees of central Europe are not halophytes. Only few tree species are salt-tolerant, but their optimal growth and development is in non-saline environments. Some tree species are tolerant in salt-spray drift and some in soil salinity (Do-Gyun 2010). In general stone fruits, conifers and young trees are highly prone to damage by salt than deciduous trees and trees older than 3 years (Kayama et al. 2003; Goodrich et al. 2009). Woody plants suffer the biggest salt stress immediately after snow melts and soil defrosts, before they start germinating in the spring. Adding humus, fertilizing with trace elements and loosening the soil will help the germinating plant to bear spring stress (Marosz 2011). Use of surface mulch before winter season will absorb majority of chlorides. Spruce (*Picea*), pine (*Pinus*), linden (*Tilia*) and maples (*Acer*) should be avoided to grow on salt-contaminated soil, and resistant species, such as poplar (*Populus*), ash (*Fraxinus*), willow (*Salix*), black locust (*Robinia*) and silverberry (*Elaeagnus*), should be preferred (Šerá 2017).

Growth and physiology of *Salix alba* × *S. matsudana* and *E. camaldulensis* were evaluated in vertical saline gradients to determine the effect of mean salinity of rhizosphere on their growth (Andriana et al. 2017). The results showed that *E. camaldulensis* growing in vertical gradients of soil salinity had leaf tolerance mechanisms, through osmotic adjustment (related or not to Cl^- accumulation) allowing it to maintain leaf function. Furthermore, there is an avoidance strategy at root level due to lower root growth in saline soil layers when they are in lower positions of the soil profile and potentially, Na^+ exclusion. Thus, the aerial growth is less affected. Whereas, the salinity gradient direction had an effect on the observed responses, being less affected when salts are present in upper compared to lower soil layers. On the other hand, *S. alba* x *S. matsudana* presented a salinity response characterized by senescence and decline of green leaf biomass. This characteristic was mainly seen in treatments with uniform salinity along the soil profile or with salt mainly located in lower soil layers. Compartmentalization of Cl^- in some leaves caused their loss, while undamaged leaf biomass maintained its functionality (Andriana et al. 2017).

23.6 Potentials of Agroforestry on Saline Waterlogged Soils

23.6.1 Productivity

The growing of different tree species leads to timber, fodder and fuelwood production and enhances the income of the farmers adopting agroforestry-based technologies. Dagar et al. (2016) determined the optimum spacing of trees in strip plantation for higher wood production, crop yield and water table draw down under waterlogged conditions. *E. tereticornis* was planted in paired rows on ridges (0.5 m height) on the field boundaries in north-south direction at 1 m × 1 m, 1 m × 2 m and 1 m × 3 m spacing resulting in population of 300, 150 and 100 trees ha^{-1}. After 6 years of growth, *Eucalyptus* recorded the maximum growth in 1 m × 3 m spacing followed by 1 m × 2 m, 1 m × 1 m and minimum in block plantation. Due to more trees per unit area, timber dry wood production was 33.5, 19.1 and 13.5 Mg ha^{-1}, and sequestration of carbon was 15.2, 8.9 and 6.4 Mg C ha^{-1} in 1 m × 1 m, 1 m × 2 m and 1 m × 3 m tree spacing, respectively. *Eucalyptus* block plantations generated 141.7 Mg ha^{-1} timber wood biomass and sequestered 66.5 Mg C ha^{-1}. Lowering of water table improved soil properties that produced 1.7 and 1.3 times higher grain yield of wheat and rice, respectively, than control. The results indicated that 1 m × 1 m spacing for strip plantation of *Eucalyptus* in paired rows on farm boundary for 6-year rotation was optimum for attaining higher wood biomass production, carbon sequestration, crop productivity and water table draw down on waterlogged fields.

23.6.2 Biodrainage and Lowering of Water Table

The high consumptive water use of plants is the main driving force behind the biodrainage concept. It is the process of draining out excess soil water in atmosphere through deep-rooted plants using their bioenergy and consists of the strategic planting of trees and other vegetation with high-transpiration potential (Khamzina et al. 2005; Dubey 2012). The absorbed water is translocated to different plant parts by xylem, and finally through transpiration, more than 98% of the absorbed water is lost into the atmosphere, and about 2% is retained by the plant itself for maintaining its turgidity. The biodrainage technology is based on combined process of absorption, translocation and transpiration of excess groundwater into the atmosphere by deep-rooted vegetation (Ram et al. 2008). Salt-resistant, high-transpirative and deep-rooted plant species should be utilized for biodrainage. The deep root characteristics of these trees make them proficient water users as compared to the crop plants (Heuperman et al. 2002). Quick-growing trees like *Eucalyptus*, with high water consumption potential under excess soil moisture condition, are preferable for biodrainage. Other preferable species for biodrainage include *Acacia nilotica*, *Terminalia arjuna*, *Pongamia pinnata*, *Casuarina glauca*, *Bambusa arundinacea* and *Syzygium cuminii*. There is a consensus that biodrainage can provide solutions to problems of seepage from canals and waterlogging. Under optimal conditions, a tree canopy may lower down water table by 1–2 m over a time span of 3–5 years (Kapoor 2000). Since biodrainage tree species are well adapted to saline root-zone environment, it is believed that they may absorb salt solutions and decrease subsoil salinity.

Biodrainage model can be applied as control measure in waterlogged lands with water levels up to 3 m and as preventive measure in lands having water table in the depth range of 3–9 m to prevent waterlogging (Parkash and Mohan 2016). Heuperman et al. (2002) reported lowering of water table by trees both in irrigated and dry land area in Victoria, Australia. In north Victorian irrigated area, *Eucalyptus* plantation (8-year old) lowered the water table by 2 m or more and reduced the piezometric head in the underlying aquifer up to 1.5 m. Heuperman and Kapoor (2003) estimated that the mean annual rate of transpiration was 3446 mm from a mixed plantations (*A. nilotica*, *P. cineraria*, *Ziziphus spp.*, *E. camaldulensis*) of 25 ha in the Indira Gandhi Nahar Project in Rajasthan during a 6-year study. It was estimated that water removal rate is equivalent to a vertical drainage network with 500 m well spacing with a 33 m^3 $hr.^{-1}$ pumping rate. Further estimations indicated that forest plantations covering only 10% of the area (1,77,000 ha) would transpire the estimated annual groundwater recharge of 2.6 billion cubic meter (BCM) which can provide satisfactory insurance against waterlogging hazards. Chhabra and

Thakur (2006) computed water balance in Karnal, Haryana, India, for 5 years and reported that *E. tereticornis* plants could biodrain 5.03-, 5.14-, 6.96- and 8.01-folds the potential evaporation in the 2nd, 3rd, 4th and 5th year, respectively. They advocated *E. tereticornis* as an excellent species for controlling water stagnation and removing excess water and for disposal of waste waters through land application. Angrish et al. (2006) advocated that there is a need to quantify the biodrainage potential of different tree species into slow biodrainers, moderate biodrainers and fast biodrainers. The fast biodrainers should be put in situation where water table is shallow and waterlogging problem is severe. On the other hand, places where sweet groundwater has gone very deep, the prospects of planting fast biodrainers like *Eucalyptus* may not be environmentally sound. Ram et al. (2011) observed that closely spaced block of *Eucalyptus tereticornis* which acts as bio-pump can lower the waterlogging and salinization in canal command of shallow groundwater in semi arid regions and boost agricultural yield. Toky et al. (2011) studied the role of *Eucalyptus* hybrid, *Prosopis juliflora*, *Melia azedarach*, *Pongamia pinnata*, *Callistemon lanceolatus*, *Tamarix articulata* and *Terminalia arjuna* planted along field boundaries on waterlogged area in the form of agroforestry to remediate the water table through efficient biodrainage. The water table in the entire site was lowered down over this period, making the land otherwise unproductive into productive and thus accessible to cultivation. Bala et al. (2014) reported that *E. rudis* could be used as an efficient biodrainage species in canal command waterlogged area of Indian desert. In addition *Tamarix dioica*, *P. juliflora* and *Saccharum munja* have come up in the area with receding groundwater table as natural succession and contributed significantly in further lowering groundwater and enhancing crop productivity. Patra and Banik (2018) discussed various problems and prospects of bioremediation of soil salinity and waterlogging for sustainable agriculture.

23.6.3 Reduction in Salinity

The planned plantation through biodrainage can help achieve water balance as well as salt balance in saline waterlogged land. This is one of the major issues to be addressed by biodrainage. Generally, the plant species selected for land reclamation are *Tamarix troupii*, *Acacia nilotica*, *Prosopis juliflora* and different *Eucalyptus* species (Tewari et al. 1997; Zhao et al. 2004). However, *Eucalyptus* plantations are best suited for potential biodrainage purpose. Other suitable species for biodrainage are *Terminalia arjuna*, *Pongamia pinnata*, *Casuarina glauca* and *Syzygium cuminii* (Toky et al. 2011). However, whether the plant takes saline water and stores the salts in the plant or roots absorb only the water leaving behind the salts is not well known. Some of the plants are pruned periodically, and cut portions are used as fodder or fuel wood. If the plants had drawn saline water, then pruning would remove some of the salts from a saline land, which would be a low cost alternative for salt removal from the soil.

Bio-amelioration with trees helps in minimizing salt deposition in the upper layers of the soil and also prevents salt accumulation on the surface layer (Tomar et al. 2003; Bahera et al. 2015). *Eucalyptus* trees can lower the waterlogging and salinity in canal command areas (Ram et al. 2011). The effects on ECe depression were more pronounced in the upper (0–15 cm) soil layer but higher in lower depths (>60 cm) in fields with plantation than the fields without plantation. They suggested that the decline in groundwater table in plantation fields would have ceased the upward movement of salts to top layers through capillaries, causing their accumulation in deeper soil layers. Therefore, biodrainage is an efficient remedial measure for waterlogging and salinity management in certain areas; it however has prolonged negative effects of salt accumulation in the root zone of tree plantation strips which is a major drawback of biodrainage adoption in arid and semi arid regions (Heuperman 1992). Bala et al. (2014) have reported high EC in top soil layers in the *Eucalyptus* plantation in canal-irrigated waterlogged area of Indian desert over 3 years. This may be due to accumulation of salts in the active root zone which is a common phenomenon in plants growing in areas with shallow water table. Salt uptake might be negligible in relation to the salts present in high salinity environments. However, under low salinity environments salt balance through uptake and removal by plants might be attainable (Heuperman et al. 2002). Chhabra and Thakur (1998) were of the opinion that plants did not accumulate salts and thus did not excavate salts from soil. In spite of some limitations, combined biodrainage system along with conventional drainage system with wider spacing seems to be viable alternative to control both water table and salinity considerably.

23.6.4 Improvement in Soil Properties Through Tree Species

Efforts have been made to identify salt-tolerant trees, shrubs and grasses for cost-effective phytoremediation of these soils without any expenditure in an environment-friendly manner. Available evidences indicate that sodic and saline soils could be made productive by growing tree plantations (Mishra et al. 2003; Qadir et al. 2007). The restoration of degraded saline and sodic soils under tree cover is attributed to gradual improvements in their physicochemical and biological properties. In most of the cases, tree cover augments the soil organic carbon and nutrient contents and brings out a gradual decrease in exchangeable sodium and soluble salt concentrations. Under tree cover, the decrease in soil bulk density is often accompanied with an increase in soil water holding capacity, porosity, permeability and water infiltration rate (Mishra et al. 2003). Due to substantial improvements in infiltration rates under tree plantations, soluble salt content significantly decreases in the upper soil layers (Nosetto et al. 2007). The higher microbial biomass pool under tree cover, probably due to organic matter addition through leaf litter, favourably enhances the soil health and productivity (Kaur et al. 2000). Sustained research efforts at ICAR-CSSRI have culminated into the development of viable agroforestry techniques and agronomic practices which hold high importance for the best productive use of large areas of salt-affected community and government lands lying abandoned due to one reason or another (Dagar et al. 2001; Singh and Dagar 2005). In waterlogged saline soils, *Casuarina glauca*, *P.*

juliflora, *Acacia farnesiana*, *A. nilotica*, *A. tortilis*, *T. articulata* and *Parkinsonia aculeata* gave good results (Dagar and Tomar 2002). Commercial plantations of these agroforestry trees in salt-affected lands could alleviate fuel wood and forage scarcities and may prove useful in sequestering carbon to moderate the impacts of climate change (Sharma et al. 2011).

23.7 Conclusions

Salts accumulate in the soils through different sources. Salts may accumulate in the surface horizons of soils mainly due to the secondary salinization associated with waterlogging, high salt content of irrigation water, release of immobilized salts already precipitated in soils, salt depositions in coastal areas, release from soil minerals and use of fertilizers. A large number of factors are responsible for waterlogging in the salt-affected soils. These include heavy rainfall and runoff accumulation, clayey soil, inadequate surface drainage, faulty water management practices, shallow water table, unlined irrigation systems, seepage from the upstream reservoirs and flat to concave land topography. These problems of waterlogging and soil salinity are common world over. Salinization and alkalization combined with waterlogging have translated a sizeable area of arable lands into less productive in different countries. The problems of waterlogging and salinity can be successfully controlled by traditional engineering-based reclamation measures such as surface and subsurface horizontal or vertical drainage with proper design and installation. But their large-scale adoption in farmers' fields is constrained due to high investment, annual operational and upkeep cost and problems of harmful drainage effluents removal leading to environmental degradation. The limitations of the conventional drainage techniques thus need to be addressed by alternative approaches to keep the agriculture sustainable over the years. Quick-growing tree species have shown potential for regulating salt-affected waterlogged situations across the varied agroecological regions in the world. Different tree species are suitable for enhancing productivity and improvement of such sites by reducing soil salinity and lowering water table through biodrainage of excess water. While designing agroforestry systems for such degraded sites, factors such as spacing of the trees, their location within a catchment, type of the tree species, method of planting, etc. should be taken into consideration. Tree density should be selected that would give a full canopy as fast as possible. However, the final leaf area attained mainly depends upon soil, climate and species performance rather than the tree spacing. Deep-rooted tree species should be preferred over shallow-rooted species. These species will be able to take and transpire water from deeper layers of soil. The tree species tolerant to waterlogged and salt-affected conditions should be planted. Ridge-trench method is best suited for saline waterlogged soils, and no other method has been found suitable for such soils. Different tree species have been found suitable for controlling salinity and waterlogging in various regions of the world.

The growing of different tree species leads to production of timber, fodder, fuelwood and other tree-based products and enhances the income of farmers adopting agroforestry technologies. Biodrainage potential of tree species leads to lowering of water table and reduction in soil salinity. Trees with high-transpiration rate, salt-resistant, fast-growing and deep-rooted should be selected for biodrainage. The strategic plantation through biodrainage can help to achieve optimum water as well as salt balance in saline waterlogged land. The restoration of degraded salt-affected waterlogged soils under tree cover is attributed to gradual improvement in their physicochemical and biological properties. In most of the cases, tree cover augments the soil organic carbon and nutrient contents and brings out a gradual decrease in exchangeable sodium and soluble salt concentrations. Together, these effects contribute the productivity enhancement of salt-affected soils. But saline agroforestry is still a hanging fruit, and its maximum potential can be extracted by adoption of saline agroforestry practices on a landscape scale in saline waterlogged areas.

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Fruit and Vegetable-based Saline Agricultural Systems for Nutritional and Livelihood Security

24

R. Banyal, S. K. Sanwal, P. C. Sharma, R. K. Yadav, and J. C. Dagar

Abstract

Food, freshwater and fuelwood requirements are increasing enormously with each passing day due to increase in unchecked world population. Feeding of rapidly increasing population with nutritious food and ensured livelihood security is the biggest challenge of the twenty first century with the prerequisite that land and water resources are limited. Nearly, 1000 million hectares area spread in more than 100 countries are affected by salinity. Moreover, rapid salinization and sodification in the irrigated landscapes are inflicting unacceptable environmental damages. These soils are universally low in fertility with saline aquifers not suitable for conventional agriculture. Soil salinity is the major stress considered under plant science stresses. The need of the hour is to develop environmentally sustainable and economically viable farming systems. Cultivation of profitable crops like fruits and vegetables in farming systems in salt-affected soils is essential for good remuneration with livelihood security. Many fruit trees such as phalsa (*Grewia asiatica*), date palm (*Phoenix dactylifera*), olive (*Olea europaea*), guava (*Psidium guajava*), chicle (*Manilkara zapota*), Indian jujube (*Ziziphus mauritiana*), jamun/jambolan (*Syzygium cuminii*), Indian gooseberry (*Emblica officinalis*), pomegranate (*Punica granatum*), karonda (*Carissa carandas*), and bael (*Aegle marmelos*) have potential for saline environment. Research on plant

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root systems can be helpful to increase salt tolerance of vegetable crops. The quantitative data in reference to most of the vegetables are limited to draw inferences between salt tolerance threshold and yield reduction. The broad categories of fruit- and vegetable-based agroforestry systems are horti-agri, horti-pastoral, and horti-silvo-pastoral in which intercrops like cluster bean, pearl millet, barley, medicinal and aromatic plants and vegetables (okra, spinach, sugar beet, cabbage, brinjal, kharif onion, muskmelon, chili, tomato), and fodder grasses can be grown individually or along with fruits and/or forest trees under the influence of saline irrigation. Creation of potential productive fodder systems through palatable halophytes is the viable option to rehabilitate saline soils along with additional income to resource-poor farmers in terms of livestock rearing. Similarly, *Manilkara hexandra*, *Morinda citrifolia*, *Pandanus*, *Artocarpus heterophyllus*, *Annona squamosa*, *A. glabra*, local banana (*Musa* spp), *Ardisia solanacea*, and *A. andamanica* are in custom among the local people in coastal areas. Vegetables and fruit crops are important to meet the nutritional requirements of the people involved in farming. Therefore, salt-tolerant fruit plants and vegetable crops provide a sensible alternative for salt-affected landscape with ecological and economic productive services. Fruit and vegetable- based potential agricultural systems for nutritional and livelihood security of the farming communities inhabiting the salt-affected areas is being discussed with recommendations.

Keywords

Fruit and vegetable-based agricultural systems · Salt-affected soils · Saline soils · Nutritional security · Livelihood security · Climate mitigation · Agroforestry

24.1 Introduction

The increase in food requirements because of burgeoning population compels to explore more land resources and bring all kinds of lands including degraded under production systems. Finite land resources are further vulnerable by the variety of resource degradation problems in order to achieve the food and nutritional security. World is confronting with the climate changes, posing the threats to natural resources, food systems, health and well being of the lives on earth. The changes in the prevailing climate with land resources can directly influence the farming system. Global food security, health, and well-being could be significantly affected without the successful reverse of the environmental changes (IPCC 2014). Populations heavily reliant on subsistence farming appear to have food insecurity in the future because of the predominance of negative influences of environmental stressors on the yield and quality of fruits and vegetables (Shrestha and Nepal 2016; Tibesigwa et al. 2015; Shisanya and Mafongoya 2016). Land resources suffered a variety of degradation including salinization which is the process of increasing salt load in the soil profile. The salt-laden soils alone have significant global dimension as about one billion hectares spread in more than 100 countries are suffering from this abiotic stress. India is also facing a similar situation and about 6.73 million hectares of land are salt-affected. Rapid salinization and sodification of land in the irrigated landscapes are resulting in unacceptable environmental damages. Poor-quality aquifer, low biological diversity, and danger of climate change have added new dimensions to the already complex problem of rational management of soil and water in salt-affected environment. As such, numerous technologies have been developed and are acceptable to the farmers both in economic and environmental perspectives.

Agroforestry is now a well-accepted integrated dynamic approach to have sustained production in resource-limited situations. Many, if not most, agroforestry systems have been developed in response to long-term interactions between agroecological conditions, plant diversity, and farmers' resource and their needs. Agroforestry in many instances addresses a basic issue in agroecology of the scarcity of productive land for agricultural pursuits. Farm diversification with fruits and vegetables can be a key to nutritional and livelihood security of the farming sector. The desired development could not be achieved because of sporadic and isolated efforts in the past. In recent times, rising incomes and globalization of trade have also caused a clear dietary shift toward protein- and calorie-rich diets which include fruits and vegetables (GOI 2007; Shetty 2002). As productive soils and freshwater are depleting, food requirements are increasing, and human diets are becoming diversified, there is no other alternative except to go for intensive farming on fertile lands with assured input facilities and also to enhance the soil productivity of marginal and degraded lands to address the twin goals of natural resource conservation and adequate food availability for the rising global population. There is limited scope for expansion in prime agricultural lands due to competition for land and freshwater use in different sectors of the economy (Pathak and Saroj 1999; Sharma and Singh 2015). The national goal of achieving 4 percent growth in agriculture can be achieved through major contribution from fruits and vegetable crops which are highly remunerative if improved management practices are adopted along with development of appropriate technology and market linkages. Fruits and vegetables are considered as rich source of nutritional security.

This chapter deals with synthesis of research knowledge on salinity/sodicity tolerances of fruit- and vegetable-based agricultural systems and examples of promising agroforestry models to improve and maximize the benefits from resource-poor salt-affected soils (SAS) to cater the nutritional and livelihood security of the mankind.

24.2 Agroforestry as Livelihood and Nutritional Security Option

The agricultural models are undergoing a shift with major focus from cereal production to diversified farming practices. Agroforestry of fruits and vegetable crops improve productivity and ensure nutritional security of the populace. Although India is the second largest producer of fruits and vegetables, the availability of fruits and vegetables to all consumers still continues to be much below the dietary requirements. There would be more emphasis on more production of fruits and vegetables due to improvemnt in per capita income with increase in health conscious population. Therefore , there is need to explore and develop new cultivars resistant to the current and future stresses due to climate change and poulation pressure. The technologies must improve the efficiency of water and nutrients. Thus, technology-driven farming systems are expected to address the concern for complementary, nutritional, and livelihood security leading to the ultimate goal of economic development.

Agroforestry is being considered as a desirable option to have change in the existing farming system toward more balanced cropping system to meet the ever-increasing demand for food, fuelwood, fiber, etc. with amelioration of salt-affected soils. About 1.2 billion people (20% of the world's population) depend on agroforestry products and services for their survival. However, over the time, with shrinking land holdings, annual crops have replaced trees for various reasons. In Indian context, more than 85 percent landholdings are in small category, out of which 67 percent have only 0.38 ha to feed their families and generate sufficient income for livelihood. Therefore, desirable intervention for the introduction of profitable crops like fruits and vegetables in a farming system is essential. Innovative approaches are found better for improving the profitability of highly location specific agricultural systems (Chand et al. 2011). It has been found that due to the holistic diversified approach, 6.8 times increase in net returns over variable cost in improved farming systems is obtained, and household consumption increased by 51.4 percent (Gangwar and Ravishankar 2015). Trees are the backbone of integrated farming systems which is necessary for self-reliance and sustainable agriculture. Besides to diverse options and products, agroforestry is also entrusted to provide employment opportunities in rural areas. There is a plethora of small-scale wood-based industries because of the assured availability of wood in the market which has been triggered in the recent past. Several fruit tree species have shown promising performance under saline environments against the inherent belief that fruit trees are usually sensitive to saline conditions.

24.2.1 Fruit-based Agroforestry Landscape

In the past, the efforts were on the utilization of salt-affected lands mainly focused to enhance the production of annual crops. Recently, the need was felt to focus the work on phytoremediation aspects with economic tree species to rehabilitate salt-affected lands and also by utilizing saline water (Dagar 2014; Dagar and Minhas 2016). The plantations of trees, namely, arjun (*Terminalia arjuna*), mesquite (*Prosopis juliflora*), shisham (*Dalbergia sissoo*), kikar (*Acacia nilotica*), khejri (*Prosopis cineraria*), common ironwood (*Casuarina equisetifolia*), eucalyptus (*Eucalyptus camaldulensis* and *Eucalyptus tereticornis*), subabul (*Leucaena leucocephala*), *Salvadora persica, Parkinsonia aculeata*, *Tamarix articulata*, and many others have shown promise in saline environment (Qureshi et al. 1993; Jain and Singh 1998; Bhojvaid and Timmer 1998; Kaur et al. 2002; Qureshi and Barrett Lennard 1998; Singh and Dagar 1998, 2005; Tomar and Minhas 1998; Tomar et al. 1998; Dagar et al. 2001b).

Fruit trees are considered to be sensitive, but hardy fruit types have the good potential for cultivation in salt-affected lands (Saroj et al. 1994; Singh et al. 1997; Dagar et al. 2001b; Singh and Dagar 2005; Dagar 2014). Nowadays these are considered as an integral component in various agroforestry systems to provide nutritional and livelihood security. A recent study showed that an overwhelming 85 percent of the global SAS have only slight to moderate constraints for crop production (Wicke et al. 2011). It has been shown that an appropriate combination of different techniques including improved planting methods, salt-tolerant cultivars, reduced amendment application, supplemental nutrition, the use of microbial inoculants, and drip irrigation makes it easier to grow fruit crops in saline soils. The potential fruit trees for saline soils are phalsa (*Grewia asiatica*), date palm (*Phoenix dactylifera*), olive (*Olea europaea*), chicle (*Manilkara zapota*), guava (*Psidium guajava*), jamun/jambolan (*Syzygium cuminii*), Indian jujube (*Ziziphus mauritiana*), Indian gooseberry (*Emblica officinalis*), karonda (*Carissa carandas*), pomegranate (*Punica granatum*), bael (*Aegle marmelos*), and many others. Date palm tolerates high soil salinity up to ECe 10.9 dS m^{-1} (Barreveld 1993). Another potential fruit tree in saline environments is olive, which is a glycophytic species which is found to avoid salinity stress through salt exclusion mechanism (Gucci and Tattini 1997). This species is usually put in moderately tolerant class with salinity aspect. However, some cultivars of olive have shown higher tolerance to saline conditions.

Melgar et al. (2009) determined long-term effects of saline irrigation on vegetative growth, yield, and fruit characteristics of mature olive trees with the background of increasing irrigation demand in olive orchards because of its high remunerative nature. They studied the effect of irrigation regimes ((i) no irrigation, (ii) short irrigation considering soil water reserves, and (iii) long irrigation without considering soil water reserves by adding 20 percent as leaching fraction) in 8-year long-term field experiment (1998–2006). *Olea europaea* cv. Picual trees were managed with drip irrigation of saline water. Three saline irrigations (0.5, 5, or 10 dS m^{-1}) were applied. The observations on growth parameters, leaf and fruit nutrition characteristics, yield, oil content, and fruit attributes were recorded on an annual basis. After 8 years of treatment, salinity did not show any adverse effect on the growth parameters and ionic concentration (Na^+ and Cl^-) in leaf. The ionic conc. Was below the toxicity threshold level of 0.2 and 0.5 percent in Na^+ and Cl^-, respectively. No salt accumulation was observed in the upper 30 cm soil layer (where most of the roots were present) because of leaching by occurrence of rains at the end of the irrigation period. Results suggest that a proper management of saline water, supplying Ca^{2+} to the irrigation water, using drip irrigation, and growing a tolerant cultivar can allow to use high-saline irrigation water (up to 10 dS m^{-1}) for a long time without adverse effect on growth and yield in olive trees for sustainable management of tree-based systems in Mediterranean regions. Similarly, Wiesman et al. (2004) evaluated the effects of three levels of saline irrigation on long-term basis on Barnea olive trees to optimize vegetative growth, productivity, and oil quality in the Negev Desert of Israel. Intermediate salinity (4.2 dS m^{-1}) gave statistically significant inhibition in growth during the first year. There was nonsignificant decline in growth attributes compared to control (1.2 dS m^{-1}) from the second year onward. However, high salinity, i.e., 7.5 dS m^{-1}, gave significant reduction in tree growth. Furthermore, the intermediate treatment led to significant increase in tree productivity compared to other treatments. No significant differences were observed between saline and control water-irrigated trees in terms of basic quality parameters of olive oil, namely, free fatty acids, peroxide value, and fatty acid profile. Saline treatments are reported to increase the levels of certain antioxidant components (polyphenols and vitamin E) in the oil compared with the control. The investigation clearly recommends that moderate level of salinity in irrigation water (4.2 dS m^{-1}) is best for olive production. Olive cultivation is effective for livelihood security of the arid and semiarid regions.

A systematic investigation on screening and evaluation of potential olive germplasm to alkalinity and salinity tolerance has been initiated at ICAR-CSSRI, Karnal, Haryana. In total, eight olive cultivars, namely, Arbequina, Barnea, Koroneiki, Picual, Coratina, Frantoio, Leccino, and Picholine, were selected for its evaluation under the influence of varying salinity regimes ECe ranging from 5 to 10 dS m^{-1} and sodicity regimes from pH 8.2 to 9.4 in quasi-controlled nursery conditions. These cultivars will be evaluated on survival, growth, and their tolerance to salt-based physiological and biochemical traits. Initial trend showed that Arbequina cultivars performed better with respect to survival and growth under nursery condition than other cultivars. The maximum survival (94%) was recorded with Arbequina and lowest (67%) in Frantoio. The order of performance of the cultivars was found to be as Arbequina>Koroneiki>Picual>Barnea> Coratina>Picholine>Leccino>Frantoio. The initial trends of the investigation indicate that this species will certainly survive in salt-affected soils which will boom the economy of the farmers. Ghrab et al. (2014) studied the long-term effect of partial root-zone drying (PRD) irrigation technique using saline water (6.7 dS m^{-1}) on olive fruit yield and oil composition. They found that PRD strategy ensured sustainable long-term yield from olive plants with minimum salt accumulation in the soil. Accumulated yield significantly increased, and oil content decreased with applied saline irrigation. Irrigation induced a trivial increase in free oil acidity, K_{232}, K_{270}, and oleic acid in comparison to rainfed conditions. Low levels of chlorophyll, carotenoids, and phenols result in little oil stability. Long-term use of saline water improved the fresh fruit yield in olive trees compared to rainfed conditions.

Raised and sunken bed techniques have been found effective in crops such as pomegranate which fail to establish under shallow water table conditions (Dagar et al. 2001a; Dagar and Tomar 2002). Guava cultivar Allahabad Safeda and Bael cultivar NB-5 have been found suitable for cultivation under saline conditions. Similarly, many pomegranate genotypes collected from Rajasthan and Punjab states have shown encouraging results in SAS. Different genotypes and species of Indian jujube such as *Ziziphus rotundifolia* and *Z. spina-christi* are being evaluated for use as salt-tolerant rootstocks (CSSRI 2015). Salt-tolerant polyembryonic rootstocks (ML-2 and GPL-3) were identified in mango (Kannan et al. 2014). The potential fruit trees which can be grown in salt-affected lands are given in Table 24.1 with their sodicity and salinity tolerance range.

Singh et al. (1997) and Dagar et al. (2001b) studied the performance of ten fruit species, namely, pomegranate (*Punica granatum*), sapota (*Achras zapota*), guava (*Psidium guajava*), bael pather (*Aegle marmelos*), jamun (*Syzygium cuminii*), aonla (*Emblica officinalis*), ber (*Ziziphus mauritiana*), karonda (*Carissa carandas*), date

Table 24.1 Sodicity and salinity tolerance of fruit trees

Ranking based on tolerance level	pH	ESP (%)	ECe (dS m^{-1})	Fruit trees
High	9.5–10.5	40–50	12–15	Ber, date palm, sapota, gular (*Ficus glomerata*), khirni (*Manilkara hexandra*)
Moderate	8.5–9.5	30–40	09–12	Gooseberry, pomegranate, ber, karonda, guava, date palm, bael, peach (*Prunus persica*), jamun, phalsa, mulberry (*Morus alba*), Kainth (*Feronia limonia*), custard apple (*Annona squamosa*), cherry (*Prunus* spp.), tamarind (*Tamarindus indica*)
Low	7.5–8.5	20–30	06–09	Fig (*Ficus carica*), guava, mango, olive, citrus
Sensitive	6.8–7.5	15–20	04—06	Banana, pineapple (*Ananas comosus*), jackfruit (*Artocarpus* spp.), litchi (*Litchi chinensis*), papaya (*Carica papaya*), passion fruit (*Passiflora edulis*), strawberry (*Fragaria* spp.), cashew (*Anacardium occidentale*), avocado (*Persea americana*), pear (*Prunus* sp.), grape (*Vitis vinifera*)

Source: Pathak and Saroj (1999) and Rajkumar et al. (2016)

palm (*Phoenix dactylifera*), and tamarind (*Tamarindus indica*) in highly alkali soil (pH 10·5) at Bichhian Experimental Farm, CSSRI, Karnal, under the influence of site preparation and application of amendment consecutively for 3 years. The analyzed treatments were site preparation (auger hole of 20–25 cm diameter and 160–180 cm deep in 45 and 90 cm^3), gypsum amendments and fruit trees. The experiment was laid out in split-plot design. Site preparation techniques and amendment did not affect survival, height, and girth of all the species. Jamun, guava, ber, and tamarind performed very well irrespective of planting techniques and amendment use. However, date palm and bael could not perform well. Initially sapota gave satisfactory growth, but in later stages, it was found highly sensitive to frost. Similarly, pomegranate which was performing well was also found very sensitive to prolonged water stagnation. Established trees found to bear fruiting between 18 and 24 months of outplanting. The technology of raising guava and bael under shallow saline water table conditions has been standardized. The plants are successfully grown on raised beds with marginal saline water (~3.5 dS m^{-1}) irrigation (CSSRI 2017). Singh et al. (2018) recommended that the cultivar NB-5 of Bael is suitable for saline soils where good-quality water is available for irrigation. They further reported the fruit-yielding traits like fruit length, breadth, and weight significantly decline in salinized plants regardless of the cultivar. Salt-stressed NB-5 cultivar not only prevented the accumulation of Na$^+$ to toxic levels but also exhibited higher K$^+$ concentration in different parts resulting in better growth in saline soils.

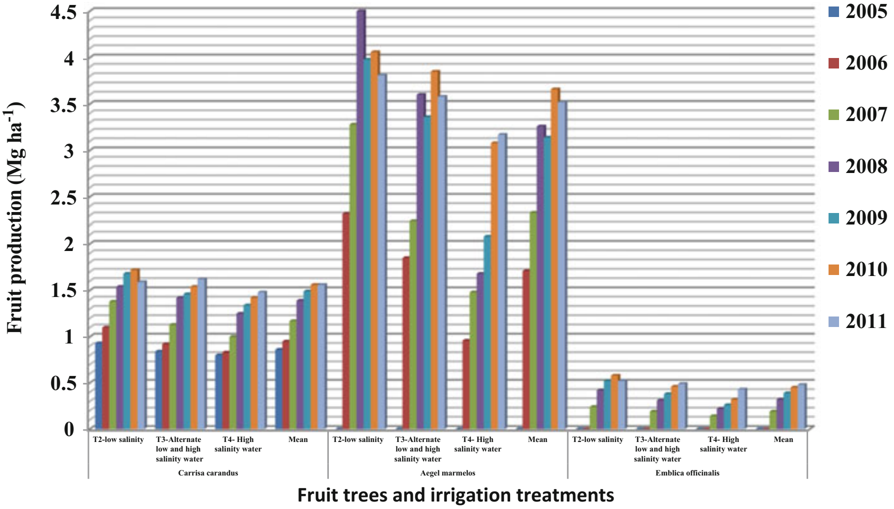
As such, fruit trees are sensitive to salinity but can be grown by using the rootstock of halophytic tree species for econmic fruit yields in saline soils with saline irrigation (Dagar and Singh 2007). *Ziziphus nummularia*, a salt-tolerant species, is better rootstock for *Z. mauritiana* which produce larger berries. Similarly, *Manilkara hexandra* is better rootstock for *M. zapota* for better fruit production. Dagar (2018) has reported several fruits of coastal areas, which tolerate salinity. *Morinda citrifolia*, well-adapted to saline water and coastal salinity, is a wonderful multipurpose tree-bearing fruits which are consumed, pickled, and used for extracting juice. *Pandanus* is staple food among coastal population of Andaman-Nicobar Islands. Fruits of *Artocarpus heterophyllus* (as vegetable and fruits), *Annona squamosa*, *A. glabra*, local banana (varieties of *Musa acuminata*, *M. textilis*, *M. paradisiaca*), *Ardisia solanacea*, and *A. andamanica* are in custom among the local people. The tuber roots of *Manihot esculenta* along with several *Dioscorea* roots are also consumed by them. Coconut (*Cocos nucifera*) is the life tree for the aborigines. Palmyra palm (*Borassus flabellifer*) is used for toddy, jiggery, vinegar, beverage, and juice for sugar making and its radicles (after germination of fruit) in coastal areas of Andhra Pradesh. Many other wild species like *Cycas rumphii*, fruits of mangrove *Avicennia marina*, fruit pulp of *Balanites roxburghii*, leaves of *Basella alba*, and fruits of *Opuntia*, *Diospyros ferrea*, *Syzygium cuminii*, *S. samatangense*, *Rhodamnia trinervia*, and *Ximenia americana* are consumed as food by locals. Other potentially useful fruit trees include species of *Lycium*, *Santalum acuminatum* (distributed widely in Australia), *Mangifera andamanica*, *M. camptosperm*, and *Coccoloba uvifera*.

The promising fruit-based agroforestry systems exacting salt-affected soils are illustrated below:

24.2.1.1 Horti-agri System (Fruit Trees + Arable Crops)

Fruit trees and agronomical crops are the main component of the system. Pathak and Saroj (1999) developed such type of model by raising 156 fruit plants ha^{-1} of *Emblica officinalis*, *Punica granatum*, *Morus alba*, *Ziziphus mauritiana*, and *Aegle marmelos* which covered 20 percent land area in the form of basin and bunds, and the remaining 80 percent could be utilized for growing intercrops. Wheat, barley, mustard, and safflower were grown as intercrops in the alley. *Sesbania* was recommended as green manure in first rainy season, and afterward intercrops were grown. The study carried out at ICAR-CSSRI, Karnal, Haryana (Dagar et al. 2008, 2016), revealed that fruit trees, namely, *Feronia limonia*, *Ziziphus mauritiana*, *Carissa carandas*, *Emblica officinalis*, and *Aegle marmelos* could be grown successfully with saline irrigation up to ECiw 10 dS m^{-1}. Cluster bean, mustard, and barley were grown as companion crops. The intercrops could be raised successfully with one or two irrigations. This has been found very viable agroforestry system for dry-land ecologies using saline irrigation.

Dagar et al. (2016) developed low water-requiring, salt-tolerant fruit-based agroforestry systems with saline irrigation for semiarid regions. The fruit trees were *Carissa carandas* (karonda), *Emblica officinalis* (aonla), and *Aegle marmelos* (bael), and the intercrops *Hordeum vulgare* (barley), *Brassica juncea* (mustard), *Cyamopsis tetragonoloba* (cluster bean), and *Pennisetum typhoides* (pearl millet) were grown in the interspaces. The fruit trees were successfully grown in the sill of furrows using low (EC 4–5 dS m^{-1}) salinity water. Consequently, all the three systems were



Source: Dagar et al (2016)

Fig. 24.1 Temporal changes in fruit production. (Source: Dagar et al. 2016)

managed under low, high (8.5–10.0 dS m^{-1}) saline, and low and high saline water alternatively. The trend of fruit yields in respective years under the influence of applied irrigation treatments has been given in Fig. 24.1. Fruit yields are reported to decline by 18 to 27.5 percent in karonda, 41.6 percent in aonla, and 31.7 to 54.8 percent in bael with alternate and high saline irrigation, respectively. Here, only the performance of cluster bean is discussed because of the significance of cluster bean as vegetable crop. In both the intervals, i.e., 2003–2007 and 2008–2011, the trend of cluster bean yield was similar. Cluster bean yield was reduced with saline water and more when intercropped with bael than karonda and aonla (Fig. 24.2.) because of the larger canopy of bael compared to other two fruit species. During initial period of fruit trees' establishment, the yield of intercrops was higher compared to later stages of fruit trees in all the systems. The production of cluster bean was low in karonda, Aonla and Bael based- agroforestry systems than the open conditions (without trees). There was consistent decline in the yield with the increase in the saline irrigation from low to high.

The soil salinity was developed in 0–1.20 m soil depth during summer after the harvest of winter crops. Soil salinity was observed to be proportional to the irrigation water salinity used in all the agroforestry systems. Soil salinity was observed to be influenced by the annual rainfall. Salts accumulated with saline water irrigation in the previous season were leached from the rhizosphere in the event of normal rainfall (~450 mm). Such observations were recorded in all the years except in 2004 and 2006, when rainfall was below the normal (321 and 340 mm), respectively. Soil salinity buildup followed an inverse linear relationship with annual rainfall in all the evaluated fruit-based agroforestry systems under specified irrigation scheduling management options which is represented by the empirical formulae, as:

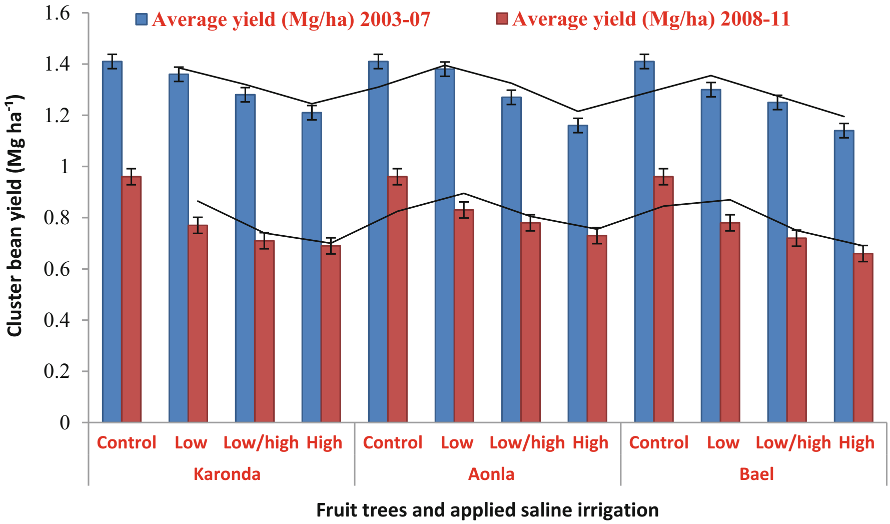


Fig. 24.2 Cluster bean yield (Mg ha^{-1}) with fruit trees. (Source: Dagar et al. 2016)

$$Y = -0.004X + 6.36$$

where:

Y represents salinity status in soil.
X represents annual rainfall.

The maximum soil salinity buildup was found to be 6.36 dS m^{-1} in the absence of rainfall and further observed to decrease by 0.4 units with every increase of 100 mm unit of rainfall.

Karonda-based agroforestry system could be a viable option for groundwater salinity of about 10 dS m^{-1}. Aonla- and bael-based agroforestry systems are relatively in demand and could be the potential system in moderately saline water situations (Fig. 24.3). The study advocates that the saline water up to 10 dS m^{-1} is beneficial to use under sustainable fruit-based agroforestry systems. Similar, fruit-based systems can be proved better to improve livelihood and nutritional security of the dry land saline situations.

Among the various soil-crop-water management options, medicinal and aromatic plants also offer viable alternative for utilizing degraded lands (Dagar et al. 2008, 2013; Tomar et al. 2010). The use of plants in the reclamation of saline landmasses is the cheapest approach. In this respect, the development of highly productive fodder systems through the palatable halophytes resulted in reclamation of saline soils besides the source of additional income to resource-poor farmers (Helalia et al. 1992; Dagar et al. 2004). The introduction of *Glycyrrhiza glabra* (liquorice) in the reclamation of saline soils and the subsequent restoration of irrigated cropping

Fig. 24.3 Cluster bean with aonla (top left) and bael (top right), and barley with karonda (bottom) cultivated with saline irrigation. (Photograph by JC Dagar)

systems has been demonstrated in several studies (Badalov 1996). The potential use of *Glycyrrhiza glabra* to reclaim abandoned saline areas was assessed over a period of 4 years before being returned to cotton/wheat crop rotation in Hungary steppe of Central Asia by Habibjon et al. (2005). They demonstrated the reclamation effect of liquorice in bringing abandoned salt-affected soils into production considered as low-cost option and could be adopted by farmers. Dagar et al. (2014) evaluated the potential of liquorice (wonderful medicinal plant) in sodic soil where it performed better than normal soils. Several species of lemongrasses like *Cymbopogon flexuosus*, *C. citratus*, and *C. pendulus*, palmarosa (*C. martinii*), vetiver (*Vetiveria zizanioides*), and many other medicinal plants, namely, psyllium (*Plantago ovata*), periwinkle (*Catharanthus roseus*), *Aloe vera*, and *Adhatoda vasica*, have been documented to be promising resources for cultivation by using saline water (Joy et al. 2006 and Dagar et al. 2008, 2013; Tomar et al. 2010). Pathak and Saroj (1999) while working on fruit-based model with medicinal and aromatic plants in sodic soils found that the aromatic grasses without application of soil amendments can be grown successfully up to 9 pH. The important hardy grass species which require less management are lemongrass (*Cymbopogon flexuosus*), palmarosa (*C. martinii*), and vetiver (*Vetiveria zizanioides*). Dagar et al. (2014) reported that these grasses can be cultivated successfully up to pH 9.4 in sodic soils. However, the *Matricaria chamomilla* (medicinal plant) can also be grown up to 9.4 pH without treating the soil. Dagar et al. (2005) established that periwinkle is a potential medicinal plant for saline conditions. Dagar et al. (2013) performed series of experiments to work out the possibility for cultivation of lemongrass in dry regions with saline irrigation and found that furrow planting method was superior and herbage production improved with increase in irrigation frequency. They further found that cultivar/varieties RRL 16, OD-58, and Praman were most promising with saline irrigation. The results indicated the possibility of raising lemongrass on degraded calcareous soils using saline irrigation water up to ECiw 8.6 dS m^{-1} without salinity buildup in soil in the event of normal rainfall. They also recommended that *Aloe vera* cultivation with trees in salty conditions is beneficial for economic gains and soil reclamation in dry situations.

24.2.1.2 Horti-pastoral System (Fruit Trees + Fodder Grasses)

Fodder grasses, namely, Kallar grass (*Leptochloa fusca*), para grass (*Brachiaria mutica*), *Chloris gayana*, and Bermuda grass (*Cynodon dactylon*), can successfully be grown with *Emblica officinalis*, *Punica granatum*, *Morus alba*, *Ziziphus mauritiana*, and *Aegle marmelos* for fodder production in alkaline soils. It is advisable not to grow Kallar grass with aonla fruit trees because of high water requirement of grass which may result in adverse effect on growth and fruiting of the trees. Kallar grass is planted by stem cuttings at a spacing of 30 × 25 cm and para grass by stem and root at spacing of 65 × 25 cm. These grasses are planted in rainy season (July to August) in all the fruit-based systems. Mulberry (*Morus alba*)-based agroforestry system can be developed for rearing of silkworms along with different fodder grasses. In this model, 2500 plants can be planted in 1-hectare area with 2 × 2 m spacing. Thicker twigs of mulberry can be used for fuelwood and thinner twigs for basket-making to enhance the economic gains of the farming communities. The interspaces of mulberry can be utilized for growing of different grasses even without treating the lands with gypsum and pyrite (Pathak and Saroj 1999).

24.2.1.3 Horti-silvo-pastoral System (Fruit Trees + Forest Trees + Grasses)

In this land-use system, fruit trees are maintained in the core zone and forest trees at the peripheral boundary of the landscape. *Casuarina*, *Eucalyptus*, *Leucaena*, *Pongamia*, *Prosopis*, etc. are to be planted at 5 m apart, while plants like *Azadirachta indica*, *Dalbergia sissoo*, *Terminalia arjuna*, *Mangifera indica*, and *Aegle marmelos* having larger canopies should be planted at 10 m spacing. Pathak (1996) emphasized that at least five plants of neem (*Azadirachta indica*) must be planted in agroforestry system for getting products especially neem oil and cake being used to control different diseases and pests of fruit trees and arable crops.

Barring few studies, the previous research work at ICAR-CSSRI, Haryana, India, was mainly on the potential utilization of fruit trees individually and not as integrated system with intercrops. With the advancement of science, current issues and future challenges of climate change compelled us to devise the strategies to have nutritional and livelihood security agricultural systems. Growing of fruit trees with economically viable arable, medicinal & aromatic crops, grasses, and vegetables is viable option to diversify the farming systems.

24.2.2 Vegetable Cultivation

Vegetables are important constituents of agriculture sector for providing nutritional and livelihood security to the masses at large and farmers in particular. Vegetable cropping is beneficial for farmers with small land holdings because an appreciably higher income per hectare can be generated compared to conventional staple crops (Genova et al. 2006). However, vegetables are generally considered sensitive than staple crops to stressful environment of extremes of temperatures, drought, salinity, alkalinity, water logging, and mineral nutrient excesses and deficiency (Chinnusamy et al. 2005). Such environmental stressors are exacerbated by the current climate changes happening in various parts of the world. The presence of high amount of soluble salts in soils limits the production of most of the crops including vegetables (AVRDC 2006). India is bestowed with diverse agro-climates and distinct seasons, making it possible to grow a wide range of vegetable crops. In an estimate, 31 percent (375 million) of Indians are vegetarian; therefore, vegetables play a pivotal role in nutrition of the vegetarian diet, especially as sources of vitamins (A, C, B_1, B_6, B_9, and E), minerals, dietary fiber, and phytochemicals. All the vegetables are free from cholesterol. In India, per capita vegetable consumption has been increased to twofold in 2012 from 120 to 230 g day^{-1} from the base year of 1999. Further increase would be expected by 2030 for fresh export and processing purposes under changing food scenario. Therefore, there is a need to explore new areas for vegetable farming especially salt-affected lands under vegetable-based agroforestry models. It is reported in the literature that individually different vegetables were evaluated for sodicity and salinity tolerances but not grown with the trees as agroforestry system, exclusively. The works of different researchers have been summarized to have the overview of the possibility to identify some of the potential vegetables to grow with trees (fruit as well as forest) in agroforestry models especially in salt-affected soils.

Salinity affects the vegetables in the form of reduction in the growth rate resulting in shorter stature and smaller and sometimes fewer leaves. Reduced roots in length, volume, and thickness (thinner or thicker) are also the result of salinity stress in plants. Maturity may be delayed or enhanced based on the type of species. The degree of growth reduction under salinity differs greatly with species and to a lesser extent with varieties within a species. The severity of salinity response is also governed by environmental interactions such as relative humidity, temperature, radiation, and air pollution (Shannon et al. 1994). Ionic effects generally damage the meristems of plants giving symptoms typical of nutritional disorders. Thus, high concentrations of Na or Cl may accumulate in leaves or portions thereof and result in "scorching" or "firing" of leaves, whereas nutritional deficiency symptoms are generally similar to those that occur in the absence of salinity. Calcium deficiency symptoms are common when Na/Ca ratio is high in soil water. All salinity effects may not be negative and may have some favorable/positive effects on yield, quality, and disease aspects. Spinach yields are initially found to increase at low to moderate salinity and thereafter decrease (Osawa 1963). Similarly, it has been reported that carrots growing under the influence of salinity gave higher sugar content. Potato gave low starch content with increase in salinity level (Bernstein 1959); cabbage heads are more solid at low salinity levels and vice versa (Osawa 1961). Celery is observed for more resistant to blackheart disease under saline conditions (Osawa 1963 and Aloni and Pressman 1987).

Mass (1990) categorized vegetables, namely, broccoli, cabbage, cauliflower, tomato, eggplant, potato, turnip, radish, lettuce, pumpkin, cucumber, and pepper, as moderately sensitive, red beet (*Beta vulgaris*) moderately tolerant, and okra, pea, onion, and carrot highly sensitive to salt. Salinity affects the growth and productivity of okra adversely, but it is put under semi-tolerant or moderately tolerant crop category compared to many other vegetable crops (Unlukara et al. 2008). Salinity (NaCl) had a considerable inhibitory effect on seed germination of okra. Sugar and phenols increased, and K^+, starch, and amylase activity decreased significantly in the cotyledons of germinating seeds (Dkhil and Denden 2010). The okra fruit production reduced to 50 percent at 6.7 dS m^{-1} salinity level (Minhas and Gupta 1993). Mangal and Singh (1993) studied the performance of a number of vegetable crops at different soil salinity levels (ECe) and found that beans are highly sensitive to salinity as their yield is reduced to 50 percent even at low ECe of 3 dS m^{-1}, whereas broccoli, cucumber, fennel, and squash are relatively tolerant as no reduction was observed at ECe of 3 dS m^1. Spinach, celery, and cabbage are highly tolerant as 50 percent reduction was observed only at high ECe of 10 dS m^1 (Table 24.2). Fennel seed yield decreased by 4.7 and 20 percent with alternate irrigation of low (4.6 dS m^1) and high (8.7 dS m^1) saline water irrigation (Yadav and Dagar 2016). The promising vegetable crops for salt-affected soils are given in Table 24.3 along with their popular varieties.

Salt accumulation in the root zone results in the development of osmotic stress and disrupts cell ion homeostasis by inducing inhibition in uptake of essential elements (K^+, Ca^{2+}, and $NO_3{}^-$) and the accumulation of Na^+ and Cl^-. Specific ion toxicities are the result of the accumulation of sodium, chloride, and/or boron in the tissues of transpiring leaves to damaging levels. The accumulation of toxic ions inhibits the photosynthesis and protein synthesis, in-activation enzymes, and damages chloroplasts and other organelles. These effects are more in older leaves because of more accumulation of such ions. Salt stress effects on root architecture are poorly understood. Root biomass is affected largely by excess salinity than aboveground plant parts. Salinity reduced root biomass in broccoli and cauliflower and root length density (RLD) in tomato (Snapp et al. 1991). Saline irrigation enhanced the occurrence of blossom end rot (nutritional disorder related to Ca^{2+} deficiency) in tomato, pepper fruits, and eggplants. However, salinity has some positive effects on the quality of the edible parts of the vegetable crops. In general, salinity increased fruit dry matter content, total soluble solids (TSS), and acid content of melon, tomato, sweet pepper, and cucumber. Salt stress increased

Table 24.2 Percent yield reduction in vegetable crops under saline environment

S. no.	Vegetables	% yield reduction			
		None	25%	50%	100%
1.	Beans	1	2	3	5
2.	Broad bean	2	4	7	12
3.	Broccoli	3	6	9	12
4.	Carrot	1	3	6	8
5.	Cabbage	2	6	10	16
6.	Celery	2	6	10	16
7.	Chili	1	4	6	11
8.	Cucumber	3	5	7	12
9.	Fennel	3	6	9	12
10.	Garlic	2	3	7	10
11.	Lettuce	1	3	5	9
12.	Muskmelon	1	4	6	11
13.	Onion	1	3	5	8
14.	Okra	2	4	6	–
15.	Pepper	2	3	7	10
16.	Potato	2	4	7	11
17.	Radish seed	2	5	8	14
18.	Spinach	2	5	10	16
19.	Sweet potato	2	4	6	10
20.	Sweet corn	2	4	6	10
21.	Squash	3	5	6	–

Source: Mangal and Singh (1993)

Table 24.3 Promising vegetable varieties for salt-affected soils

S. no.	Crop	Variety/line	S. no.	Crop	Variety/line
1.	Brinjal	Black beauty, R-34	7.	Garlic	HG-6
2.	Cabbage	Golden acre	8.	Okra	Pusa Sawani, Kashi Kranti, VRO-112
3.	Muskmelon	Pusa Madhuras	9.	Peas	P-23, new line perfection, market prize
4.	Kharif onion	Basant	10.	Potato	JE-808, Kufri Chamatkar, CP-2059, JE-303, Kufri Sindhuri
5.	Onion	Hisar-2, Punjab selection, Udaipur-102, Bombay red, Pusa Ratnar	11.	Tomato	EC-2791, DT-10, EC-13904 and C-11-2, hybrid 14, NT-3, Marglobe, Kalyanpur, T-1, Sabour Suphala, at-69, Hisar Arun, Moneymaker
6.	Chili	C-4, Musalwadi, Jwala, Chaman			

carotenoid content and antioxidant activity of tomato (De Pascale et al. 2015). Nutritional quality (e.g., glucosinolate, polyphenol content) of the edible florets of broccoli was improved under moderate saline stress. The timing of application of salt stress directly influences the vegetable yield and quality, considered to be important for improved irrigation and fertilization management practices. In two melon cultivars (Galia and Amarillo Oro), the application of salt stress from fruiting to harvest did not reduce marketable fruit yield but increased the fruit quality (TSS) and maturity index in both cultivars (Botía et al. 2005).

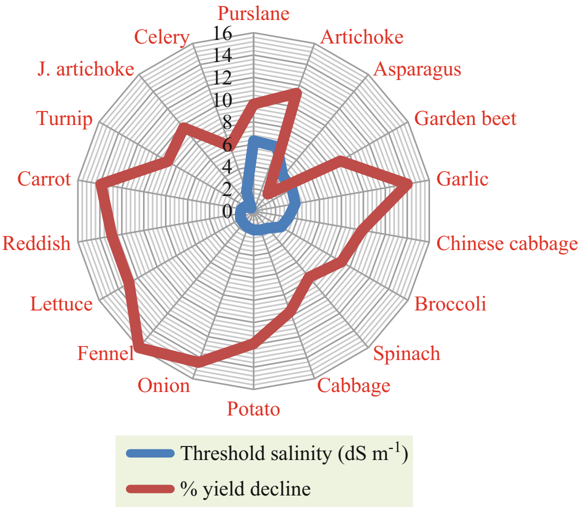
Shannon and Grieve (1999) summarized the information about the salt tolerance of common vegetable crops by categorizing them into herbaceous species grown for human consumption in which the edible portions consist of leaves (lettuce, cabbage), swollen tap roots, (carrot), lateral roots (sweet potato), hypocotyls (radish, turnip), aboveground stems (asparagus), belowground stems (Irish potato, Jerusalem artichoke), petioles (celery), and flower buds (globe artichoke, cauliflower). They worked out on general tolerance to salt and ions that are commonly associated with saline soils and waters.

They reviewed the data set of different experiments to have the salinity threshold tolerance with percent yield reduction of 18 vegetable crops (asparagus, purslane, garden beet, Chinese cabbage, broccoli, spinach, celery, turnip, Jerusalem artichoke, artichoke, garlic, cabbage, potato, lettuce, radish, carrot, onion, and fennel) (Fig. 24.3). Purslane crop gave the highest salinity threshold tolerance (6.30 dS m^{-1}) and the lowest (0.35 dS m^{-1}) with *J. artichoke*. There was 16 per cent yield decline of Fennel crop than the rest of the vegetable crops. It was the highest among all the tested vegetable crops. Here, the highest resistant crop in terms of percent yield reduction was asparagus which gave only 2 percent reduction. Asparagus is the most salt-tolerant commercially available vegetable crop and grows better in sandy, well-drained soils than heavy-textured soils. Francois (1987) reported 2 percent yield reduction per unit with increase in soil salinity (ECe) above the threshold level of 4.1 dS m^{-1}. Salinity increased the total soluble solids in spears. The effect of salinity on yield was more severe in the second cropping year due to carry-over effects on the root mass. Mills (1989) reported based on the results of in vitro study of the asparagus that tolerance is directly related to cellular organization and organogenesis with rooted and unrooted plantlets. Graifenberg et al. (1993) categorized the fennel crop as sensitive to NaCl salinity. This crop gave 16 percent yield decline with the increase in the unit of salinity level. Tolerance parameters for fennel bulb yield and plant fresh weight were expressed in terms of electrical conductivity of the irrigation water (ECiw) and saturated extract (ECe) of soil. Varietal differences were slight. Fennel bulbs accumulated more Na and Cl compared to leaves and roots. The authors had speculated that Na induced K deficiency in bulbs and resulted in growth reduction. *Jerusalem artichoke* is rated as sensitive to moderately sensitive to salinity treatments. The salt tolerance threshold level was (ECe) 0.4 dS m^{-1}. Chloride in stems increased with salinity but Na in leaves remained low. Purslane is rated as moderately tolerant with salinity threshold of 6.3 dS m^{-1}, and percent yield reduction was 9.60 percent. The crop is cultivated commercially in Mediterranean regions for salad (Kumamoto et al. 1990). However, after the first cutting, the halophytic nature of purslane is expressed, and its salt tolerance increased with subsequent harvests (Grieve and Suarez 1997). Potato is rated as moderately tolerant to salinity. It is highly sensitive during tuber bud initiation which reduces the proportion of large tubers preferred commercially (Paliwal and Yadav 1980). Tuber size is reduced with the increase in salinity level but its number is not declined. There is a decrease in the average potato tuber size with the increase in salinity duration and/or concentration. It is also noted that salinity did not significantly affect the quality or percentages of reducing sugar, sucrose, and starch in tubers. Even no injury symptoms on potato leaves were observed.

Onions are salt sensitive and relative excluders of Na and Cl. Tolerance in onion is high at germination, very low at seedling growth, and high at three to five leaf stages. Leaves change color from rich green to dull blue green under salt stress. Leaf tip burn symptoms typically associated with salinity stress were also seen. Yield declined at ECe of 1.5 dS m^{-1} up to 14.45 percent (Fig. 24.4). It is also observed that salinity decreased bulb diameter, bulb weight, root growth, plant height, and the number of leaves per plant. Onions get mature a week earlier when grown under saline conditions. Pasternak et al. (1984) hypothesized that sensitivity in early growth stages is due to underdeveloped shallow rooting system of young ones. They also indicated that there is a need to devise research experiments to determine whether the rooting systems are the base or not to improve salinity tolerance. Francois (1994) recommended that the threshold salinity level of garlic is 3.9 dS m^{-1} which declined yield up to 14 percent (Fig. 24.4). They reported that all yield attributes, viz., bulb weight, diameter, plants per unit area, and percent solids, were reduced with the increase in salinity. Shoot dry weight was less sensitive to salinity compared to bulb weight.

Although it has been observed that there is availability of information on salt tolerance of common vegetables, it is also pertinent to say that quantitative salt tolerance data are limited for several vegetables, namely, cauliflower, kale, Brussels

Fig. 24.4 Salinity threshold tolerance with percent yield decline of vegetables. (Source: Shannon and Grieve 1999)



sprouts, kohlrabi, cress, water cress, and rutabaga and several of the others like horseradish and sea kale. Moreover, no information is available pertaining to salt tolerance of bamboo, basil, cardoon, celeriac, chayote, chervil, chicory, coriander, cress, dandelion, endive, ginger (rhizome), horseradish, jicama, leek, spinach, radicchio, rhubarb, roselle, rutabaga, salsify, sea kale, scolymus, scorzonera, water chestnut, and yam. Therefore, there is need for research in this area. The apparent genetic diversity among vegetables to accumulate a range of different ions and their combinations could add to the significance of these species as bio-accumulators. There is a growing need to use poor-quality water for agriculture which include both saline groundwater, agricultural drainage, and municipal and industrial wastewater.

24.2.2.1 Horti-agri System (Fruit Trees + Vegetables)

It is well documented that cultivation of vegetables is possible in relatively fertile soils having pH <9.0. Before growing any vegetables with trees (*Emblica officinalis*, *Punica granatum*, *Morus alba*, *Ziziphus mauritiana*, and *Aegle marmelos*) on salt-affected patches, it is essential to grow *Sesbania* as green manure and add 15 Mg ha^{-1} of FYM followed by plowing. The crops like okra, spinach, sugar beet, cabbage, and tomato are grown in trenches 30 cm wide and 22 cm deep, while bottle gourd, pumpkin, parwal, brinjal, tomato, and other cucurbits can be grown in pits of 45 cm^3 after filling with soil and FYM in 1:1 ratio (Pathak and Saroj 1999). In one trial on sodic soils, fodder-Egyptian clover, wheat, rice, onion, and garlic were cultivated successfully for 3 years along with fruit trees, namely, karonda, pomegranate, gooseberry, guava, jamun, and ber. From intercrops 10.6–10.8 Mg ha^{-1} forage, 1.6–3.0 Mg ha^{-1} grains from wheat, 1.8–3.4 Mg ha^{-1} onion bulb, and 2.3–401 Mg ha^{-1} garlic were harvested in different years showing the potential of giving remunerative crop yield during establishment phase of planted fruit trees (Tomar et al. 2004).

The ICAR-Central Soil Salinity Research Institute, Karnal, Haryana, developed different fruit-based agroforestry systems which are being practiced by the farming communities of the region. The systems comprised of bael (*Aegle marmelos*), aonla (*Emblica officinalis*), and karonda (*Carissa carandas*) as tree components and cluster bean (in kharif) and barley (in rabi) as subsidiary components which were found practically and economically feasible with the moderate (ECiw 4 to 5.8 dS m^{-1}) to high salinity (ECiw 8.2 to 10.5 dS m^{-1}) water used for irrigation in dry climate (Dagar et al. 2008, 2016). Green vegetables such as *Amaranthus* (*A. viridus*, *A. spinosus*), *Chenopodium album*, and climber *Asparagus racemosus* are found reasonably tolerant to soil and water salinity. These can successfully be grown in agroforestry mode. Raw fronds of mustard (var. CSR 56 and CSR 58 are tolerant to salinity) and green pods of cluster bean are used widely as vegetables, which in turn are found feasible to be grown using saline water for irrigation as has been discussed above. Please also see Ismail et al. (in this volume) who have mentioned interesting plants used as vegetables.

24.2.2.2 Silvi-agricultural System (Forest Tree + Vegetables)

The attention is being paid across the globe to identify the salt-tolerant species of economic importance for highly saline degraded areas. Growing of forest and fruit trees, grasses, and nonconventional crops of high economic value including medicinal and aromatic plants on salt-affected soils or using saline water for irrigation is a sustainable option of utilizing these degraded habitats. This model is practiced in waterlogged saline soils of Indo-Gangetic Plains of Haryana state. Farmers planted clonal *Eucalyptus* in waterlogged saline soils in blocks and also as strip plantations along with vegetables (Fig. 24.5) such as brinjal and cucurbits and even green gram to have intermittent additional income from the same piece of land. *Eucalyptus* plantations are done with an objective to draw down the water table to make the soils free of excess water which results in waterlogging situations. When the water recedes from the surface and subsurface soil layers, then the arable crops can be grown on such soils. *Eucalyptus* plantations are beneficial to bring abandoned waterlogged saline lands into productive functions.

Hasan (2006) conducted experiment on the effect of *Eucalyptus* on brinjal grown in different planting distances and found that the wider spacing (open fields) gave higher (2.5 kg per plant) yield. He observed that there is inverse relation with the yield of the inter crop brinjal with planting spacing. Bhat (2015) recommended cultivation of vegetable crops in combination with trees like *Melia composita*, especially during winter season for better economic return from the agroforestry practices. However, during summer season, a decrease in growth and yield parameters of tomato and capsicum within the agroforestry system probably indicates intense competition for critical resources like water, nutrients, and photosynthetically active radiation. Soil chemical properties, namely, soil organic carbon, pH, EC, and nutrient availability, were improved under agroforestry system than sole crop system. The availability of nutrients like N, P, and K was high where higher doses of organic manures were applied in agroforestry system as well as in sole crop system.

Fig. 24.5 *Eucalyptus*- and vegetable-based agroforestry system in waterlogged saline soils in Haryana. (Photo: JC Dagar and Surender Lathwal, DFO Haryana Forest Department)

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Integrated Farming System Approaches for Managing Saline and Waterlogged Ecologies

25

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Abstract

Increasing population and urbanization along with soil salinization, land degradation and global warming are threatening the food security in large parts of the world. In saltlands, osmotic effects of salts owing to poor soil physical conditions lead to poor aeration, nutrition imbalances and toxicities which constrain plant growth. Integrated production systems have the potential to reduce soil salinity and waterlogging through interactions among crops, trees and livestock. Most smallholder practises integrated farming that constitutes low input use and provides ecological security either by producing food, fruits, fodder and vegetables or by improving soil conditions. In developing countries like India, integrated farming system is mostly operated by the smallholders, and one or more forms of mixed agricultural enterprises are present on these smallholdings. Integrating various agricultural enterprises provides higher and regular cash incomes with respect to food, especially when the crops fail, and thus ensures greater buying power to smallholders. Moreover, diversified production is of special relevance in the context of expected climate change effects experienced by many countries in the form of frequent crop failures. The integrated agriculture system has potential to provide a risk avoidance mechanism through alternate sources of employment and income generation to rural poors. The integrated farming system is one of the most vital technologies in conserving resources and energy at farm level, besides a source of regular income to the smallholders in problematic areas. Environmental quality being ensured by recycling of farm wastes and other by-products within different components. This chapter deals with the findings of the assessments of the integrated farming system approaches for salt-affected and waterlogged areas and

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discusses the feasibility and potential for upscaling and commercialization of these technologies to smallholders in the domain area.

Keywords
Integrated farming system · Resource recycling · Salt-affected lands · Waterlogging · Small and marginal land holders

25.1 Introduction

Threats to global food security in most of the agricultural regions of the world are increasing with depleting natural resource base and due to changing climate (IPCC 2007). In the context of such growing threats, the effectiveness of diversified farming systems at mitigating the risk of crop failure bears significant relevance. Smallholders practise diverse crop-livestock farming systems in many parts of Asia and Africa, which combine different components on the farm; crops provide grain for human consumption and fodder to feed livestock, and in turn livestock provide milk for improved nutrition and manure to supply nutrients to the soil. Integrated farming system provides synergies between cropping systems and livestock which helps in increasing productivity and resource use efficiency (Herrero et al. 2010). In India, 64.8% are marginal and 18.5% are smallholders who own less than 1 ha and between 1 and 2 hectares of land, respectively, from the total of 129.22 million land holders. Integrated farming system involving one or more forms of mixed components is mostly done by the smallholders. In South Asia, ~80% of the holdings are below 0.6 ha (Gulati 2002).

The Indo-Gangetic Plain (IGP) of South Asia is characterized by lowest per capita availability of land, inequitable agrarian structure and resource-poor farmers (Singh et al. 2011). In any agricultural production system, recycling of natural resources should be the major objective in designing farming systems and agriculture policies (Senthilkumar et al. 2012). Continuity of rice-wheat system in IGP of India has raised serious concerns on degradation of soil health and shrinking fresh water resources. About 1900 million ha of land is affected by land degradation at global level (Oldeman 1994), and soil salinization and water logging are among the main causes which render arable lands unproductive (Eswaran et al. 2001; Lal 2001). Integration of various farm enterprises in the form of diversified farming system may offer sustainable solutions to these problems, especially for the increasing number of smallholders in the region. The subsistence farmers mainly depend more on annual crops, while many small land holders in the tropics have long been practicing these sustainable production systems to enhance economic conditions while ensuring their requirement to meet F5 (food, fruit, fodder, fibre and fuel). Integrating various enterprises provides higher and regular cash incomes with respect to food, especially when the crops fail, and thus ensures greater buying power to smallholders. The integrated agriculture system has potential to provide a risk avoidance mechanism through alternate sources of employment generation and income creation to the rural poor (Balooni 2003; Puri and Nair 2004; Samra et al. 2005). In such systems, round-the-year availability of the diverse products (food grains, fruits, vegetables, spices, etc.) not only ensures food diversity but also contributes to food sufficiency during the lean periods (Kumar and Nair 2004). The availability of mineral nutrients through diverse food products from the system is also improving the household nutritional security especially for women and children. In farm, families practising mixed species integrated agricultural system have significantly higher production and consumption of nutritious fruits and vegetables compared to families practising specialized agriculture system (Shankar et al. 1998). The produce quality is also expected to be superior in the produce from this system as negligible chemicals are used. Thus, a substantial unexploited potential for enhancing farm income is represented by the smallholder mixed integrated agriculture system.

This chapter deals with the evaluation of the potential of these integrated production systems in enhancing food and nutritional security and averting environmental degradation with particular reference to the role of such system in increasing the farm productivity in saline and waterlogged areas. The case studies of integrated agriculture systems undertaken by ICAR-Central Soil Salinity Research Institute, Karnal (India), are especially mentioned to demonstrate the relevance of such systems for smallholders of saline and waterlogged regions of Indo-Gangetic Plain.

25.2 Extent of Salt-affected Soils

Soil is a natural body which evolved by combined influence of climate and organisms on parent materials and conditioned by relief over a period of time. India has 2% land resources of the world and supports the world's 18% human and ~16% livestock population. However, with its diverse climatic conditions and topography, India is capable of producing a large number of crops, fruits and other vegetation. The total geographical area (329 Mha) of India is represented by different types of soils all across the country which are given in Table 25.1.

Salt-affected refers to soils that are saline or sodic in nature, and the area is increasing over the years with the climate change effects. In the world, almost 6% of the total world's land is affected by salinity or sodicity as per FAO Land and Plant Nutrition Management Service. A large proportion of world's cultivated land is prone to be salt affected. Of the current 45 Mha of total irrigated (230 Mha) and 32 Mha of total dry land agriculture (1500 Mha) is affected by varying degrees of salts. Almost 6.73 Mha of India's land is affected by salinity and sodicity and likely to be increased by 15 Mha by 2030 (Table 25.2).

Table 25.1 Dominant soil groups of India

Soils	Area (Mha)
Red and laterite soils	117.2
Black soils	73.5
Alluvial soils	58.4
Desert soils	30.0
Other soils {salt-affected soils, forest and hill soils, peaty and marshy soils}	49.6

Table 25.2 Salt-affected soils in different regions

Regions	Total area (Mha)	Saline soils (Mha)	(%)	Sodic soils (Mha)	(%)
Asia, the Pacific and Australia	3107	195	6.3	249	8.0
Europe	2011	7	0.3	73	3.6
Latin America	2039	61	3.0	51	2.5
Near East	1802	92	5.1	14	0.8
North America	1924	5	0.2	15	0.8
Total	12,781	397	3.1	434	3.4

Source: FAO Land and Plant Nutrition Management Service

Salt-affected soils in India are mainly confined to arid, semiarid and subhumid (dry) regions and also in the coastal regions. These soils vary in nature from saline to sodic based on the carbonate and bicarbonates of sodium, sulphate and chloride of calcium and magnesium. In coastal areas, salt intrusion through sea water results in saline soils which are characterized by high EC (>4 dS m^{-1}), low ESP (<15%) and low pH (8.2). The National Remote Sensing Agency (NRSA), Hyderabad, in association with the National Bureau of Soil Survey and Land Use Planning, Nagpur, ICAR-Central Soil Salinity Research Institute, Karnal, All India Soil Survey and Land Use, Delhi, and government agencies from respective states, conducted a survey to prepare salt-affected soil map of India in 1996. The salt-affected soils were categorized as per pH, electrical conductivity (EC) and exchangeable sodium percentage (ESP). The salt-affected soils were mapped at a scale of 1:250,000 using Landsat satellite images. Images were interpreted with field verification data taken for soil characterization. The distribution of salt-affected area in India is given in Table 25.3 which shows that Gujarat, Uttar Pradesh and Maharashtra account for about 62.4% of total salt-affected area. Out of the total 6.73 Mha (2.1% of the geographical area) of salt-affected soils, 2.96 Mha are saline and the rest 3.77 Mha are sodic in nature. Almost 25% (2.35 Mha) of the Indo-Gangetic Plain (10.6 Mha) is affected by salts which are mostly sodic in nature (1.79 Mha).

25.3 Waterlogged Soils

In waterlogged areas, high water table saturates the soil pores in crop root zone which restricts normal circulation of air resulted in decline of oxygen level and increase of carbon dioxide level. When groundwater table is so high to conveniently permit an anticipated activity, like crop cultivation, soil may be treated as waterlogged. The harmful impact of water table depends upon the type of crop and soil and the quality of underground water. It may vary from 0 m for rice, 1.5 m for other cultivable crops and more than 2 m for horticultural and forestry. Waterlogging is mainly accompanied by soil salinity in irrigated agroecosystem as these soils prevent leaching of soluble salts. From practical point of view, a working group constituted by the Ministry of Water Resources has suggested the following norms:

Table 25.3 Extent and distribution of salt-affected area in India (ha)

State	Saline	Sodic	Total
Andhra Pradesh	77,598	196,609	274,207
Andaman and Nicobar Islands	77,000	0	77,000
Bihar	47,301	105,852	153,153
Gujarat	1,680,570	541,430	2,222,000
Haryana	49,157	183,399	232,556
Karnataka	1893	148,136	150,029
Kerala	20,000	0	20,000
Madhya Pradesh	0	139,720	139,720
Maharashtra	184,089	422,670	606,759
Orissa	147,138	0	147,138
Punjab	0	151,717	151,717
Rajasthan	195,571	179,371	374.942
Tamil Nadu	13,231	354,784	368,015
Uttar Pradesh	21,989	1,346,971	1,368,960
West Bengal	441,272	0	441,272
Total	2,956,809	3,770,659	6,727,468

Source: NRSA and Associates (1996)

Depth to water table (m)	Nomenclature
<2	Waterlogged
2–3	Potentially waterlogged
>3	Safe

In arid and semiarid regions, introduction of irrigation facilities created the development of waterlogging and soil salinization. A total estimated area of 10–33% of total irrigated lands is affected by waterlogging and soil salinization in various countries of the world. It is estimated that the area under waterlogging and soil salinization is increasing at a pace of 3000–4000 ha per annum since 1979–1980. In India, almost 4.5 Mha is affected by waterlogging problem (Table 25.4).

25.4 Integrated Farming System: Pilot Studies for Saline and Waterlogged Areas

25.4.1 Distribution of Area Under Different Components of the System (Layout)

To improve the agricultural productivity and profitability of partially reclaimed sodic soils, a study on diversified farming system was carried out at ICAR-Central Soil Salinity Research Institute (CSSRI) Karnal, India, in reclaimed sodic soils. Subsequently, pond-based integrated farming system based on land modification (physical land reclamation) concept was targeted at the farmer's field in Sharda Sahayak Canal

Table 25.4 Distribution and extent of waterlogged and salt-affected area in India (000′ ha)

State	Waterlogged area			Salt-affected area			
	Canal commands	Unclassified	Total	Canal commands	Outside canal	Coastal	Total
Andhra Pradesh	266.4	72.6	339.0	139.4	390.6	283.3	813.3
Bihar	362.6	NA	362.6	224.0	176.0	Nil	400.0
Gujarat	172.6	311.4	484.0	540.0	372.1	302.3	1214.4
Haryana	229.8	45.4	275.2	455.0	NA	Nil	455.0
Karnataka	36.0	NA	36.0	51.4	266.6	86.0	404.0
Kerala	11.6	NA	11.6	NA	NA	26.0	26.0
Madhya Pradesh	57.0	NA	57.0	220.0	22.0	Nil	242.0
Maharashtra and Goa	6.0	105.0	111.0	446.0	NA	88.0	534.0
Orissa	196.3	NA	196.3	NA	NA	400.0	400.0
Punjab	198.6	NA	198.6	392.6	126.9	NA	519.5
Rajasthan	179.5	168.8	348.3	138.2	983.8	NA	1122.0
Tamil Nadu	18.0	109.9	127.9	256.5	NA	83.5	340.0
Uttar Pradesh	455.0	1525.6	1980.6	606.0	689.0	Nil	1295.0
West Bengal	NA	NA	NA	Nil	NA	800.0	800.0
Total	2189.4	2338.7	4528.1	3469.1	3027.0	2069.1	8565.2

Note: NA means data not available; Source: Singh (1994) command in Raebareli, Uttar Pradesh. Similarly, integrated cultivation of crops and fish using available fresh and brackish water in waterlogged coastal area was also evaluated at Canning Town, West Bengal. These pilot studies explored the synergies of integration of different possible components of farming systems and evaluated their role to enhance food access and availability and increase household incomes and employment of smallholders in salt-affected areas.

At ICAR-CSSRI, Karnal, out of the total 2.0 hectare study area (average land holding in the region), 1.0 hectare was allocated to grain crops and 0.2 hectare to each of fodder, vegetables, horticulture, fish pond and livestock+ poultry with biogas plant and compost pits. The allocations of different crops/agricultural enterprises adopted in the integrated farming system at Karnal are described in Table 25.5. Fruit trees like guava, banana, papaya, crane berry (karaunda) and Indian gooseberry (aonla) were planted on pond dykes, and understory inter-spaces between these plants were used for raising seasonal vegetables round the year.

The total 1.0 ha area at Kashrawan (Raebareli, U.P.) comprised of fish pond, field crops, fruit crops, forages and vegetable components on 0.40, 0.25, 0.15, 0.10 and 0.10 ha area, respectively. Initially, pond treatment for soil sodicity has been done for fish farming. The flat beds of pond embankment and raised beds in remaining area were utilized for raising field crops and horticultural plantations. While the embankment slopes and raised beds were used for eucalyptus plantation, which served the purpose of bio-shield and bio-drainage. At CSSRI, RRS, Canning Town, an area of 2.3 ha was reshaped into five different models, viz., paddy cum fish (PCF) in 0.51 ha, 0.51 ha under PCF for brackish water (PCF-B), 0.36 ha under farm pond (FP), 0.22 ha in deep ridge and furrow (DF) and 0.21 ha under shallow furrow and medium ridge (SF) with 0.51 ha area under original land (C) to create the scope of multicropping on monocropped land. Various rotations of field crops, vegetables and fruits along with paddy cum fish and fresh water fish in pond were taken as against single crop of rice (*Kharif*) in control. Each component was evaluated at the field and

Table 25.5 Different crop/agricultural enterprise rotations followed within each production system

Crop components		Horticulture		Subsidiary components	
Grain production	Fodder	Vegetables	Fruit trees	Livestock/ poultry	Fisheries
Area in hectare					
(1.0)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Rice-wheat: 0.2 Rice-wheat-mung bean: 0.2 Maize-wheat-mung bean: 0.2 Winter maize-soybean: 0.2 Pigeon pea-mustard-fodder maize: 0.2	Sorghum-berseem	Cabbage-tomato-khira: 0.1 Bottle gourd-cauliflower/potato-onion-okra: 0.1	Guava + papaya + banana	3 Buffaloes +2 cows +120 birds	Catla Rohu Mirgal Common carp Grass carp

farm level for its profitability, sustainability and resource use efficiency in comparison to prevalent rice-wheat or rice-rice at (Canning Town) system for respective years of studies.

25.4.2 Income and Employment Generation from Integrated Farming Systems

At CSSRI, Karnal, the productivity in different components of diversified cropping system was worked out on the basis of marketable produce from 2007–2008 to 2014–2015. It represents the yields of individual components in terms of grain, green fodder, vegetable and fruit in case of grain crops, fodder crops, vegetables and fruits, respectively (Table 25.6). In food-grain production, the highest system productivity in terms of rice equivalent yield (REY) was recorded with rice-wheat-mung bean cropping system (12.2 Mg ha^{-1}) followed by rice-wheat (11.1 Mg ha^{-1}) and maize-wheat-mung bean (7.0 Mg ha^{-1}). However, the lowest rice equivalent yield (3.7 Mg ha^{-1}) was recorded in winter maize-soybean cropping system with low net returns of ₹9815 because of foggy weather conditions which resulted in frequent attack of diseases (mildew, blights and rusts) during flowering to ripening of soybean. Under grain production components, rice-wheat and maize-wheat-mung bean cropping systems were comparable with each other in terms of production and profitability.

The average net income from crop and subsidiary components together was ₹348,595, out of which ₹72,020 came from crop (including fodder), ₹35,880 from vegetables and fruits and ₹195,650 from subsidiary components from an area of 2.0 ha, which was substantially higher than conventional rice-wheat cropping system (₹302,250). Among all the systems, fruits and fisheries production were found more remunerative with a B/C ratio of more than 4, whereas vegetable production system generated lowest B/C ratio (1.9) due to involvement of higher input cost and labour in this system.

The economy was worked out on benefit-cost analysis of the individual cropping systems in the integrated farming system at Kashrawan (Raebareli, U.P.). The B/C ratio of the integrated farming system was 2.21 despite guava and Indian gooseberry not being yielded by this time. A highest (2.63) and lowest (1.70) B/C ratio was recorded with fish farming and fruit-based system, respectively (Table 25.7). The initial investment (₹250,000) for digging the fish pond is not included in cost estimation.

Economics of various land shaping models at CSSRI, RRS, Canning Town (W. B), were calculated, and farm pond model emerged as the most profitable with the highest B/C ratio of 2.41 followed by deep furrow (DF) and paddy cum fish (PCF). All the land shaping models have been generating higher net returns over the control plot (Table 25.8).

The higher net return from diversified multi-enterprise agriculture system comes from synergistic effect among various enterprises resulting in reduced overall costs of production. These observations are consistent with the findings of earlier studies

Table 25.6 Average rice equivalent yields (REY) and income generated by various components from their respective area during 2007–2008 to 2014–2015 at CSSRI, Karnal

Component	Area (ha)	REY (Mg ha^{-1})	Gross income ₹	Expenditure ₹	Net income ₹	B/C ratio
Rice-wheat	0.2	11.1	49,075	18,850	30,225	2.6
Rice-wheat-mung bean	0.2	12.2	54,145	19,630	34,515	2.8
Maize-wheat-mung bean	0.2	7.0	31,135	11,700	19,435	2.7
Winter maize-soybean	0.2	3.7	16,250	6435	9815	2.5
Pigeon pea-mustard-maize	0.2	4.3	19,175	8710	10,465	2.2
Fodder	0.2	4.4	19,305	6695	12,610	2.9
Vegetables	0.2	6.4	28,210	14,625	13,585	1.9
Fruit trees	0.2	6.6	29,315	7020	22,295	4.2
Livestock	0.2	67.7	299,130	134,550	164,580	2.2
Fisheries	0.2	9.3	41,015	9945	31,070	4.1
Enterprise mix diversification	2	13.3	586,755	238,160	348,595	2.5

Table 25.7 Income generated by various components from their respective area during 2007–2008 at Kashrawan (Raebareli) UP

Component	Area (ha)	Gross income ₹	Expenditure₹	Net income₹	B/C ratio
Rice-wheat	0.25	10,103	5235	4868	1.93
Forage	0.10	2228	1198	1030	1.85
Vegetable	0.10	7472	2989	4483	2.50
Fruit	0.15	2100	3600	–	1.70
Fish	0.40	42,840	16,254	26,586	2.63
Total	1.00	64,743	29,276	36,967	2.21

(Chan et al. 1998). The reduced net return variability and income was due to extended trade-offs among various agricultural enterprises.

Diversified farming system generated a daily net income of ₹ 950–1000 to meet the day-to-day expenditure of the farmer's family throughout the year that reduces input dependence from outside markets and increased income to the small farmers. This system helped in generating the employment for the farm family. It can generate the 875 man-days employment round the year; however, rice-wheat cropping system can generate only 300 man-days employment from the same area. By adopting this system, we were able to generate 575 more man-days per year than the conventional rice-wheat system. Enterprise mix diversification is a way to get intensive use of family labour. This relatively assured income and employment over the years is also a result of maintaining extra enterprises such as livestock that create as well as utilize

Table 25.8 Economics of land-shaping-based diversified farming system at CSSRI, RRS, Canning Town, West Bengal

Land shaping model	Area (ha)	Operational cost and return (*Kharif* + *rabi*) (₹)			B/C ratio
		Gross income₹	Expenditure₹	Net income₹	
Control	0.51	22,510	18,292	4218	1.23
PCF	0.51	129,804	60,798	69,006	2.14
PCF-B	0.51	407,888	206,383	201,505	1.98
FP	0.36	144,676	60,112	84,564	2.41
DF	0.22	150,771	64,665	86,106	2.33
SF	0.21	141,326	72,550	68,776	1.95

the farm labour and also reducing the sourcing of short-term labour at busy times by reducing the total size of a single specialized enterprise. An increased livestock numbers need the additional cost of labour, and the benefits accruing from integration (fodder production) are compromised (Doole et al. 2009).

In diversified farming system, farmer must optimize the allocation of limited farm resources such as land, labour and capital among the enterprises on the basis of available resources, biophysical and socio-economics to get the maximum relative marginal cost of these resources. Each enterprise has its own on-farm or off-farm constraints, and increment of a particular enterprise to a large specialized farming level needs a significant capital cost and that can also change the degree of integration among other enterprises. In this system, the trade-offs are very much intermingled within the system which helped in reducing the dependency on market, and thereby higher net income was recorded as compared to conventional rice-wheat system. The increase in productivity and resource use efficiency of integrated farming system as a result of the synergies between cropping and livestock husbandry was also reported by Thornton and Herrero (2015). The efficient utilization of synergies between different enterprises in this farming system is one way to assist resource-poor farmers through improved access and availability to food, reduced dependence on outside market inputs and enhanced income. Further this farm enterprise integration reduces resource depletion and increases system adaptability to cope with climate variability under socio-economic settings (Lemaire et al. 2014).

25.4.3 Soil Health and Quality

Soil chemical and physical properties were found positive due to recycling and integration of resources available within the farm. Net increase in major nutrients (nitrogen and phosphorus) was recorded in all the cropping systems (Table 25.9). Integrated nutrient management helped in regular nitrogen build-up under different cropping systems. The nitrogen and phosphorous build-up in most of production systems was the result of using pond water for irrigation, FYM and biogas slurry. Nutrient balance in most of the cropping systems was positive, more so in the case of

Table 25.9 Changes in soil chemical properties in various production systems after 7 years of study

Cropping systems	Year	pH	EC (dS m^{-1})	OC (%)	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
Grain production	Initial	8.3	0.28	0.14	106.0	24.8	300.0
	Final	8.3	0.48	0.35	138.5	36.4	188.1
Fodder production	Initial	8.2	0.35	0.14	103.5	26.8	301.5
	Final	8.1	0.33	0.58	133.3	20.8	214.3
Horticulture production	Initial	7.9	0.41	0.14	121.0	24.2	379.9
	Final	8.1	0.30	0.98	128.1	39.8	253.1
Vegetable production	Initial	7.7	0.46	0.14	123.0	28.1	409.0
	Final	7.7	0.49	0.23	135.9	49.1	324.0
Pond dykes	Initial	10.3	4.00	0.14	55.3	15.0	213.5
	Final	9.0	0.93	0.35	120.2	18.9	294.8

Table 25.10 Initial soil properties of experimental site at Kashrawan village in Raebareli (UP)

Depth (cm)	pH (1:2)	EC (1:2) (dS m^{-1})	SAR	Na (meq l^{-1})	CO_3 (meq l^{-1})
0–15	9.84	1.98	98.6	60	40
15–30	9.45	1.22	76.5	35	24
30–45	9.20	0.98	45.7	29	16
45–60	8.97	0.97	38.6	28	14
60–90	8.73	0.79	32.8	22	10
90–120	8.57	0.68	25.6	18	8
120–150	8.50	0.55	17.8	14	6

N and P. There was slight increase in soil organic carbon (OC) percentage in all production systems. The OC (%) in horticulture production system was increased from 0.14 to 0.98 in 7 years.

The Kashrawan village in Raebareli (UP) represents a semiarid sub-tropical climate, with mean annual rainfall of 880 mm mostly (~80%) occurring during June to September. This area is known for poor drainage and outfall conditions. The experimental site is highly sodic in nature and has silty clay loam soil and poor drainage condition and is indurated with calcareous hard bed at some places between 30 and 80 cm soil depth. The salient soil characteristics are given in Table 25.10.

The soil salinity build-up at land shaping-based diversified farming system at CSSRI, RRS, Canning Town, West Bengal, in dry months was due to the upward capillary flow of water from the brackish groundwater table present at shallow depth, and the salinity of which increased with the progress of dry season (Fig. 25.1).

Besides rainwater harvesting, the different land shaping models raised a portion of low-lying land (raised land and ridges) with excavated soil, the combined effect of which improved drainage of land and reduced the salinity build-up in soil of raised land/ridges during the dry months. The soil salinity varied with the land shaping models, maximum being in PCF and minimum in raised lands/ridges of different

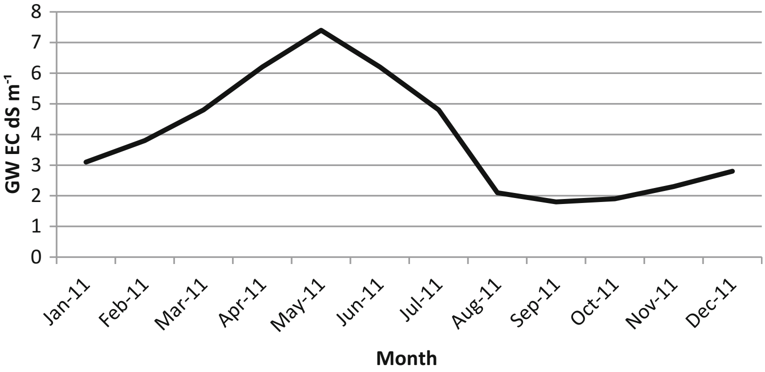

Fig. 25.1 Groundwater salinity (EC dS m^{-1}) at shallow depth measured through piezometer

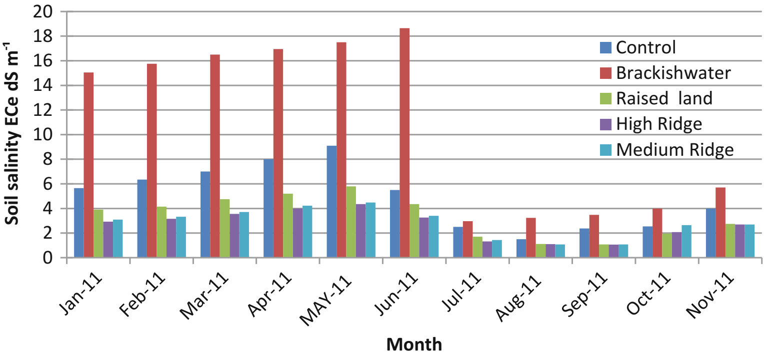

Fig. 25.2 Soil salinity (Ec_e dS m^{-1}) build-up at different land shaping

models (FP, DF, SF, PCF) compared to control (Fig. 25.2). The soil salinity build-up was very high (ECe 15- > 18 dS m^{-1}) in PCF-B in May to June compared to control (ECe 8–10 dS m^{-1}), while the raised land of other land shaping models varied between ECe 4 and 6 dS m^{-1}. The reduced soil salinity, improved drainage conditions and better availability of irrigation water provided a scope for wider crop choice and higher crop intensity/productivity. The salinity (ECe) of PCF-B model also came down to 2–3 dS m^{-1} due to initial washing by monsoon rains which provided a scope for growing normal rice crop during *Kharif* season.

Integration of legumes in the grain and fodder production systems can contribute to soil nitrogen availability through nitrogen-fixing abilities. In berseem-sorghum crop rotation, plants do not utilize all the nitrogen fixed, and some part will remain in the roots that are left behind in soil and thereby contribute to subsequent crops. The natural resource consumption particularly mineral fertilizer use is certainly reduced in the agricultural production systems that promote crops and livestock integrations (Herrero et al. 2010; Lemaire et al. 2014). The livestock production either as a supplier of nutrient in manure or as a driver of mineral fertilizer demand through feed crop consumption plays the key role in global nutrient cycles (Matsumoto et al. 2010; Senthilkumar et al. 2012). Part of nitrogen fixed in the legume fodder will eventually return to the soils as manure as root residues or fodder is fed to livestock. When this nitrogen of legume-fed livestock returned to the soil at the start of the growing season, the quality of manure will be improved, therefore contributing more towards soil fertility maintenance. Inclusion of legume crop in fodder production system helped in providing the proteins and carbohydrate in a balanced proportion that resulted in healthy and disease-free animals. Because the legume fodder is allowing livestock to improve utilization of the low-quality forage by providing nitrogen to the rumen microbes (Ezeaku et al. 2015). Further, the integrated nutrient management by use of livestock manure will provide more balanced nutrients to plants due to its lower N/P ratio (Withers et al. 2015). Recycling of farm wastes and pond water helped in improving the soil health, but the improvement seems slow and steady.

25.4.4 Resource and Energy Conservation for Environmental Quality

Integrated farming system helps in conserving natural resources and energy at farm level and provides regular employment and income to the small and marginal farmers. Recycling of available farm wastes and by-products from different components ensures soil health and environmental quality. Precise information of water requirement from individual components as well as from systems helps in formulating water management strategies to use available water resources judiciously in the integrated farming system. *Gobar gas* plant (run from cow dung) is an integral part of the integrated farming system which supplies fuel energy for domestic uses. Information on energy for both cooking and electricity generation could be gathered to estimate energy budgets to meet out farm energy requirements fully or partially. Electricity generation through solar system can also be practiced in the integrated farming system. In the integrated farming system developed by CSSRI, the fruit plants and vegetable crops grown on the pond dykes were irrigated by solar energy-based drip irrigation system. Resource recycling and physiochemical transformations involve gas exchange across the farm enterprise components. Collection of precise observations on gaseous fluxes across the model components provides deep insight into energy balance at farm level. In integrated farming system, conservation of natural resources in conjunction with judicious use of available farm resources ensures environmental quality and restores ecosystem sustainability.

25.5 Upscaling and Commercialization of Integrated Farming System

The integrated farming system developed at CSSRI has a wide potential for upscaling and commercialization in Indian sub-continent and other developing countries because of its suitability to small land holders. After evaluating it at institute level, efforts are targeted to demonstrate at farmers' fields for its adoption. Most of the components of integrated farming system model are covered under subsidy scheme of the Government of India to attract the attention of small and marginal farmers. Integration of farming system model with Indian Government scheme e.g., MNREGA, RGKVY, IRDA, Food Security Mission, etc., will definitely help in upscaling and commercialization. Rural developmental schemes related to use of nonconventional source of energy, rural electrification, rural sanitation, etc. can be easily linked with this model for its wider coverage. The rural youth can be attracted by providing the options for value addition through processing and creating good marketing outlets and by integrating with other rural enterprises. Capacity development programmes related to integrated farming system to rural youths in general and women in particular help in rapid upscaling of the model. CSSRI Karnal can act as a nodal agency for formation of guidelines for commercialization of this model in target areas and also to impart training to all stakeholders. In its present form, the farming system model provides opportunities to earn regular income and source of livelihood by ensuring food and nutritional security to small and marginal land holders besides its ecological and socio-economic benefits. However, continued research efforts on selection of enterprises will always be required for improvement and upscaling of the farming system in accordance with agroecological zones so that subsistence farming of today may become prestigious farming of the future.

25.6 A Way Forward

Salinity and waterlogging must be accepted as a global challenge as it poses threats to infrastructure, biodiversity and ecosystem. This paradigm shift in thinking is now happening related to management of natural resources by the agricultural producers, and they are also rewarded by agencies for this noble cause, as we rely on them not only for food, fruit, fodder, fibre, etc. but also to provide clean water and air, to reverse soil degradation, to tie up carbon, to conserve wildlife habitats and to maintain the aesthetic, cultural values of the land. The cost of agricultural production systems at the required scale will be many times more to tackle the salinity and waterlogging around the globe than the world community is currently ready to pay. The ecosystem services in the current situation is in its infancy, economic models can tell us about the catchment, and downstream users are paying for integrated farming systems and what they might get in return. Such models should encourage to pay appropriate share of the costs by public and private sectors. Identifying areas of preferential leakage, mixing different agricultural enterprises, using groundwater and phase farming required to protect newer area from salinity and waterlogging. The policymakers also must integrate this type of systems in watershed development programmes and help farmers in developing these systems for their livelihood. We may achieve the goal of doubling farmer's income by adopting such systems.

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Use of Poor-quality Water for Agricultural Production

26

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Abstract

Freshwater resources are being squeezed all over the world because of shifts in climate patterns, and a severe shortage of water is the major threat to food security. Most developing countries are overpopulated, and the quality and quantity of food available for these ever-increasing populations are questionable. Wise distribution of freshwater among different stakeholders is a prerequisite, giving priority to domestic use. For agriculture, wastewater of a suitable quality should be used with proper treatment and good management practices. A huge volume of wastewater is being generated, which must be properly managed for use in growing different crops. Similarly, farmers use groundwater as a supplementary source of surface water for irrigation. Unfortunately, most groundwater is brackish because of high salinity and/or sodicity. In this chapter, alternative sources of irrigation water are identified and their compositions are addressed comprehensively. It has been indicated that most alternative water sources are of low quality, and their use in agriculture demands continuous management and monitoring. Different available options are focused on, especially those acceptable to farmers, because resource-poor farmers are mostly concerned with economics. These management choices include alternative irrigation with canal water, conjunctive use of wastewater with good or marginal water, use of different organic and inorganic amendments, etc. Case studies have evaluated economic use of poor-quality water with canal irrigation. This chapter provides insights into opportunities and challenges for effective use of poor-quality water in agriculture.

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Wastewater · Poor-quality water · Groundwater · Salinity · Resource-poor farmers · Conjunctive use

26.1 Introduction

The scarcity of conventional water resources, due to climate change, is a well-documented problem nowadays. Approximately 40% of the world's population has suffered from severe water shortages (Alcamo et al. 2017). Climate change and pollution caused by anthropogenic activities have considerably reduced the quantity of water available. Furthermore, climate change caused by desertification has intensified the lack of freshwater sources in cities and rural areas throughout the world (FAO 2012). Unfortunately, this water scarcity leads to food scarcity, since 70% of the water is used for agricultural purposes (EarthTrends 2013).

To counter this, water-scarce countries will have to improve their nonconventional water resources (e.g., wastewater) to resolve water scarcity and irrigate crops (Clinton 2007; Dillon et al. 2009). Application of wastewater in agriculture is regarded worldwide as an alternative resource for irrigation to mitigate the shortage of water. However, despite adoption of many approaches, the handling of this resource remains delicate and prone to failure. It requires special attention, as wastewater treatment is lacking or is insufficient to achieve an acceptable standard that assures safe reuse (Alidina et al. 2014).

Climate change and a poor water management system have caused Pakistan to be a water-deficient country, although it has the world's largest irrigation system. This resulted in a decrease in water availability from 5300 m^3 $person^{-1}$ $year^{-1}$ in the 1950s to 1100 m^3 $person^{-1}$ $year^{-1}$ in 2014, and the availability is estimated to drop further to <1000 m^3 $person^{-1}$ $year^{-1}$ by the year 2025; 1000 m^3 $person^{-1}$ $year^{-1}$ is considered the threshold level. At a global level, water availability was 16,800 m^3 $person^{-1}$ $year^{-1}$ in 1950 and 6000 m^3 $person^{-1}$ $year^{-1}$ in 2014 (IWMI 2015). Wastewater from domestic and industrial use is released directly into natural drains, nearby fields, and septic tanks in Pakistan. The application of untreated wastewater in agriculture is increasing, although biological treatment processing is performed only in major cities of Pakistan (Islamabad and Karachi), where only a small fraction (<8%) of wastewater is treated before reuse (Ensink et al. 2004).

26.2 Generation and Reuse of Low-quality Water

In Pakistan, about 0.876×10^9 m^3 $year^{-1}$ of wastewater is used for agricultural purposes in an area of 32,500 ha (Murtaza and Zia 2012). The World Health Organization (WHO) estimates that nearly 20 million hectares throughout the world are irrigated using wastewater (WHO 2006). Mostly, the water used is untreated, as only 8% of the total generated wastewater is treated at primary level in developing, low-income countries like Pakistan. Conversely, developed, high-income countries have 70% wastewater treatment capacity (Sato et al. 2013). Therefore, decisive and large-scale actions are needed, as with the population explosion and increasing living standards, greater volumes of wastewater are produced by domestic and industrial users (Qadir et al. 2007; Asano et al. 2007).

The expansion of urbanization and climate change have led water-scarce cities and industries to reuse and recycle wastewater at a cost of about USD 12.2 billion in 2016 and an estimated cost of about USD 22.3 billion by 2021 globally (Wilson 2016). Hence, the reuse of wastewater is a key factor in human and environmental health in developing countries (Yadav and Dagar 2016). Moreover, the Organization for Economic Co-operation and Development (OECD) has estimated that wastewater generation in 2020 will be 45% greater than that in 1995. In this scenario, it is imperative for us to minimize the impacts of wastewater on the environment and reuse it extensively as a new energy resource (SUEZ e-Mag 2016).

26.2.1 Benefits of Wastewater

The application of wastewater in agriculture has both beneficial and negative impacts (Qadir et al. 2007). The wastewater used for irrigation is valued by farmers mainly because of its nutrient content and reliability of supply (Ensink et al. 2004: Murtaza et al. 2010). This reuse of wastewater exerts positive impacts on agriculture, monthly income, and employment, despite its adverse effects on soil physical and chemical properties in addition to contamination of the human food chain and related health risks (Qadir et al. 2010; Hanjra et al. 2012; Keraita et al. 2010; Sposito et al. 2016). Soil chemical, physical, and biological properties change dramatically during short- and long-term wastewater irrigation. Its impacts on humans, soil, and the environment are summarized in Fig. 26.1.

26.2.2 Wastewater Treatment

The presence of organic, inorganic, and microbial pollutants in wastewater necessitates its prior treatment to reduce their harmful effects on soil, crops, and humans. The international water quality criteria for irrigation include certain laws and restrictions for each country, which define the extent to which wastewater has to be treated (Kretschmer et al. 2002). This includes two treatment processes. Primary treatment involves coagulation of waste material with sediments or aerobic/anaerobic processes in stabilization ponds. This process is applicable for crops that are not intended for direct human consumption, whereas in secondary treatment, wastewater undergoes biological (disinfection) processes, which are recommended for almost all crops (WHO 1989; Shelef and Azoz 1996).

The US Environmental Protection Agency (USEPA), in coordination with the US Agency for International Development (USAID), published guidelines for

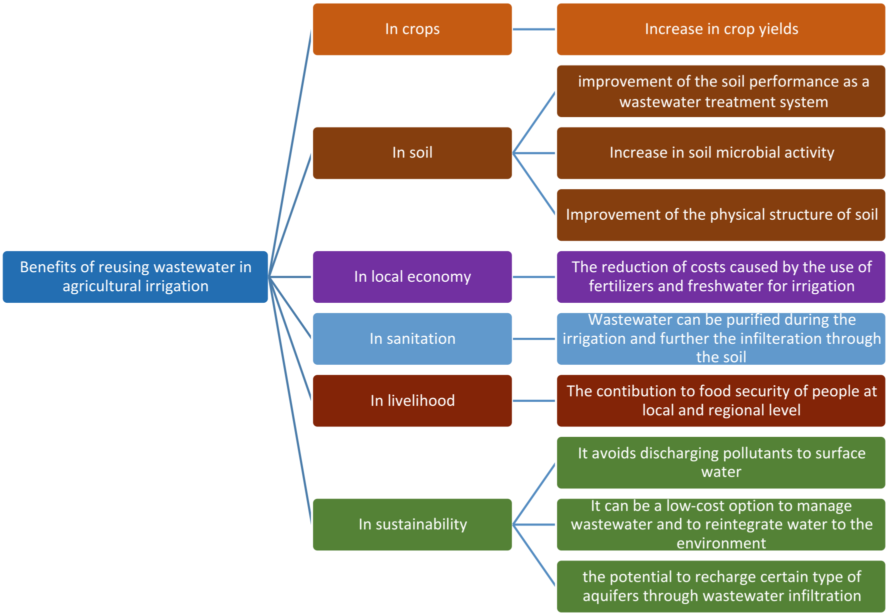

Fig. 26.1 Impacts of wastewater irrigation on biosphere equilibrium

wastewater reuse in 1992. These standards have served as guidelines for areas where there are no regulations yet. The USEPA criteria are summarized in Table 26.1 (USEPA 2004; USEPA 2012).

26.2.3 Wastewater Quality Concerns

Wastewater quality can be determined by various chemical, physical, and biological parameters. The Oregon Water Quality Index (OWQI) defines wastewater quality ratings (see Table 26.2) based on temperature, dissolved oxygen, biological oxygen demand, pH, and ammonia, phosphorus, and fecal coliform parameters (Dunnette 1979).

Water resource quality defines the subsequent uses and inherent risks of wastewater. Considering the types of low-quality wastewater applied in developing countries, the quantity and quality need to be analyzed against potential reuse and quality requirements (UNEP 2005). This is needed to guarantee acceptability for end users and to mitigate the risks to practitioners and the environment.

However, the quality of low-quality wastewater supplied for irrigation of crops may or may not satisfy the quality requirements for downstream reuse, entailing various risks to end users and consumers if it is not well managed. Improvement of wastewater quality after conventional secondary treatment can be achieved via several options—known as “nontreatment”—which are generally applied in

Table 26.1 US Environmental Protection Agency (*USEPA*) treatment and quality criteria for water reuse

Treatment	Process required	End use
Primary	Sedimentation	No uses recommended
Secondary	Biological oxidation and disinfection	Surface irrigation of orchards and vineyards
		Non-food crop irrigation
		Restricted landscape impoundments
		Groundwater recharge of nonpotable aquifer
		Industrial cooling processes
Filtration and disinfection	Chemical coagulation, biological or chemical nutrient removal, filtration, and disinfection	Landscape and golf course irrigation
		Toilet flushing
		Vehicle washing
		Food crop irrigation
		Unrestricted recreational impoundment

Table 26.2 Ratings of water quality according to the Oregon Water Quality Index (*OWQI*)

OWQI score	Rating of water quality
90–100	Excellent
85–89	Good
80–84	Fair
60–79	Poor
0–59	Very poor

countries where treatment is not available (WHO 2006). Oil mills and slaughterhouses discharging effluent into the sewer system may also cause problems for the treatment process and lower the quality of the wastewater (because of the presence of feathers, oily substances, etc.).

Heavy metal concentrations in low-quality wastewater are below the threshold values fixed by the National Standards of Reuse (Bahri and Mahjoub 2007; DGGREE 2015). However, some elements are occasionally present in high concentrations in wastewater-irrigated areas of Faisalabad and Kasur in Pakistan. For example, chromium (Cr) levels of up to 7.3 mg L^{-1} were detected in 2003 and were probably caused by discharge from tanneries and textile industries. Additionally, high concentrations of Cr (up to 76 mg kg^{-1} of dry matter) were found in soils fertilized with biosolids, whereas the value permitted by the EU Commission is 60 mg kg^{-1} of dry matter (Berglund and Claesson 2010).

To improve the quality and mitigation of toxic elements, several biosorbents/amendments have been devised. A few of them are presented in Table 26.3.

Table 26.3 Organic and inorganic biosorbents that enhance the quality of low-quality wastewater

Variable	Effect
Organic matter	Its humified form can be reduced by more than 90%, while its less humified form can be adsorbed, chelated, or volatilized
Nitrogen	It can be removed through soil transformation processes or assimilation by soil fauna and flora
Phosphorus	It is removed by plants through assimilation of ≤ 1 mg L^{-1}
Microorganisms	Soil microbial processes depend on soil physical and chemical properties; moreover, soil organic matter content also affects exogenous microbes
Heavy metals	Metal content loads can be minimized by adsorption/complexation reactions on soil and humate particles
Toxic organic compounds	Toxic compounds in soil can persist for a considerable time and then biodegrade at differential rates

26.2.4 Health Impacts of Wastewater Application

A number of bacterial, fungal, and viral diseases can emerge from wastewater application. Many pathogens, including protozoa and helminth eggs, have sufficient resistance to tolerate advanced secondary or tertiary wastewater treatment processes (Hanjra et al. 2012). However, the impacts and hazards of pathogen exposure should be minimized by use of comparatively low-quality wastewater that meets the regulatory standards set by the particular area/country. The WHO (2006) has set a standard of 1000 fecal coliforms per 100 mL for all general crops but recommends strict removal of helminth eggs.

26.3 Management of Low-quality Wastewater

Despite the health issues associated with use of wastewater, farmers value the presence of organic matter, beneficial microbes, and essential macro- and micronutrients in low-quality wastewater and their positive effect on agricultural soils (Table 26.4). However, poor understanding, poor management, and injudicious use of low-quality water without adherence to national laws limit its use (Murtaza and Zia 2012). Periurban areas and their adjoining areas have a critical demand for low-quality water (WHO 2006; Murtaza et al. 2010). Moreover, water scarcity has led to realization of the importance of water for industrial and agricultural activities. The majority of industrial entities are aware of the importance of waste management and reuse of low-quality water. So, there is a need for timely treatment of low-quality wastewater prior to its consumption (SUEZ e-Mag 2016).

26.3.1 Composition of Low-quality Water

Wastewater contains a variety of biodegradable materials (organic matter), inorganic matter (dissolved minerals), and micronutrients. However, the presence of heavy

Table 26.4 Effects of sewage effluent on nutrient and heavy metal concentrations in soil (Butt et al. 2005)

	Concentration (parts per million)							
Soil depth (cm)	N	P	Fe	Mn	Zn	Cu	Pb	Ni
0–15	0.19	300	131.87	105	166.48	17.53	4.4	0.88
15–30	0.13	95.5	96.88	43.44	120.85	5.16	2.4	1.19
30–60	0.12	144	44.38	26.4	55.87	1.25	1.62	0.88
60–90	0.15	79	27.5	14.22	39.38	1.72	0.75	0.37
90–120	0.13	55.75	31.88	13.13	124.85	3.78	0.87	0

Table 26.5 Composition of untreated city effluent collected from a suburban area of Faisalabad, Pakistan (Ahmad 2007)

Parameter	Range	Critical limit
pH	7.04–9.88	–
EC (dS m^{-1})	0.72–5.64	1.00[a]
SAR	3.76–36.17	10.00[a]
RSC ($mmol_c$ L^{-1})	Trace–25.80	2.50[a]
Cd (mg L^{-1})	0.001–0.018	0.01[b]
Cr (mg L^{-1})	0.01–2.40	0.10[b]
Cu (mg L^{-1})	0.04–0.75	0.20[b]
Fe (mg L^{-1})	0.27–3.95	5.00[b]
Pb (mg L^{-1})	0.01–1.19	5.00[b]
Mn (mg L^{-1})	0.12–1.88	0.20[b]
Ni (mg L^{-1})	0.02–0.59	0.20[b]
Zn (mg L^{-1})	0.02–0.34	2.00[b]

$n = 156$ samples

EC electrical conductivity, *RSC* residual sodium carbonate, *SAR* sodium adsorption ratio

[a] Critical limits of irrigation water quality as prescribed by US Salinity Laboratory Staff (1954)

[b] Critical limits of irrigation water quality as prescribed by Ayers and Westcot (1985)

metals, nutrients, inorganic chemicals (e.g., benzene, phenol, cyanide, fluoride, endocrine disruptors, pharmaceutical products, etc.), and toxic pathogens in wastewater may disrupt many biological and physiological processes in soil and plants (McBride 1995). The composition and concentrations of the aforementioned materials depend on their origin and source of generation (Table 26.5). Long-term irrigation using wastewater enriched with organic irrigation matter not only improves the physical and chemical properties of soil but also accelerates soil microbial activities and speeds up soil pollutant degradation (Murtaza and Zia 2012).

26.3.2 Use of Low-quality Water

Globally, around 20 million hectares of agricultural land are irrigated using low-quality wastewater, only 10% of which is treated using primary/secondary treatment processes (WHO 2006).

Farm-based measures can play an important role in reducing risks related to wastewater reuse, especially in countries where treatment is rather decentralized or of low efficiency. Participation of the public in use of treated wastewater with end users is regarded as good practice because it may encourage provision of a better service (Keraita et al. 2010). Other aspects can also be features of good practice, such as the role played by institutions and enforcement of regulations, where they exist.

Mostly, cash crops being grown in suburban areas with use of wastewater include vegetables and fodder sold in nearby urban markets. In one study, sufficient concentrations of major nutrients were found, as a result of wastewater application, at a 0.40-m soil depth in Faisalabad, Pakistan, as presented in Table 26.6 (116–195 kg ha^{-1} for N, 7–21 kg ha^{-1} for P, and 108–249 kg ha^{-1} for K) (Ibrahim and Salmon 1992). Importantly, P obtained from wastewater sources is in a 100% soluble form rather than in an insoluble form as is present in chemical fertilizers. Moreover, Murtaza et al. (2010) reported that the available form of NP fertilizer from wastewater application exceeds the requirement of most crops. Hence, larger amounts of NPK fertilizer are delivered to the soil (140–920% for N, 20–790% for P, and 125–930% for K), than the recommended levels, causing toxicity (Ensink et al. 2002) and lodging of crops due to excessive nitrogen.

Despite having different concentrations, wastewater from different sites is enriched with organic and inorganic compounds. It has been recommended that farmers practicing wastewater irrigation apply only phosphorus fertilizer, i.e., either two 50-kg bags of single superphosphate or one 50-kg bag of diammonium phosphate per hectare.

It has also been estimated that wastewater irrigation could provide about 75% of the chemical fertilizer requirements of farm crops (Murtaza et al. 2010). By minimizing the cost of chemical fertilizers, farmers could spend more money on other farm expenses, including insecticide costs, labor hire, and land rent. For example, the land rent of wastewater-irrigated land in Pakistan is PKR 150,000 ha^{-1},

Table 26.6 Nutrient concentrations in sewage effluent in different drains in Faisalabad, Pakistan (Ibrahim and Salmon 1992)

Nutrient		Drain location			
		Ghulam Muhammad Abad	Satiana Road	Jaranwala Road	Jhang Road
N (mg L^{-1})	Mean	48.85	29.25	29.05	45.45
	Range	38–66	13–48	18–44	18–71
P (mg L^{-1})	Mean	5.20	1.35	2.10	3.45
	Range	3–7	Trace–4	1–3	Trace–6
K (mg L^{-1})	Mean	62.30	38.80	26.85	48.00
	Range	49–74	28–47	20–48	33–65
N, P, and K (kg ha^{-1}) supplied through sewage effluent (4000 m^3 ha^{-1})					
N		195.40	117.00	116.20	181.80
P		20.80	6.60	8.30	13.76
K		249.20	155.20	107.90	192.20

versus a land rent for canal water–irrigated land of PKR 65,500 (PKR 123 = USD 1). The major input cost for regular farmers was the cost of fertilizer and, although this was a substantial cost, on average the total costs for regular farmers were less than those for wastewater-using farmers. However, the average gross margin for a wastewater-using farmer (PKR 10,000 ha^{-1}) was substantially higher than that for a farmer using canal water (about PKR 2500 ha^{-1}), because of higher cropping intensities and the ability to cultivate crops with higher market values.

26.4 Economic Effects of Low-quality Water in Agriculture

From an economic point of view, by adopting proper water and agronomic management practices, farmers can achieve higher yields, have surplus water available for irrigation, and save money on fertilizer costs. The application of wastewater is mostly favored in developing countries such as Pakistan because of the presence of essential plant nutrients and the low cost of wastewater (Murtaza and Zia 2012; Qadir et al. 1999). In 2004, Ensink et al. (2004) reported that in Pakistan, the average gross margin for a wastewater-using farmer (USD 173 ha^{-1}) was substantially higher than that for a farmer using canal water (USD 43 ha^{-1}). This was due to higher cropping intensities and the ability of wastewater-irrigated soil to grow cash crop vegetables, especially early in the season. Hence, in areas of water scarcity, use of wastewater for irrigation creates a win–win situation for both the systems that are responsible for wastewater disposal and the end user farmers, who thereby have the availability of a reliable water supply (WHO 2006).

26.4.1 Farmers' Perceptions About Social Impacts and Constraints of Wastewater Irrigation

In Pakistan, groundwater is becoming expensive and unaffordable for small farmers because of increasing Petroleum, Oil, & Lubricants (POL) prices and electricity shutdowns. As a result of unscheduled electricity shutdowns, more water is being used for irrigation. Sometimes, the same piece of land has to be irrigated twice [personal observation of the authors]. Mostly, the wastewater generated in urban and periurban areas is used directly for irrigation without any treatment. Besides, farmers are forced to use untreated wastewater, as they have no alternative source of water for crop production. There are a number of wastewater-irrigated sites around Faisalabad, as summarized in Table 26.7.

Farmers along the length of Channel-4 were interviewed about utilizing full wastewater or mixed wastewater, and farmers not utilizing water from this canal were also interviewed. It was reported by wastewater users that "full" application of Channel-4 wastewater (without any treatment) to wheat and sorghum resulted in severe "burning" of the crops, which led to the need for expensive replanting. It was found that long-term irrigation with Channel-4 wastewater resulted in physical deterioration of the soil and caused salinity. In addition, the formation of a compact

Table 26.7 Wastewater-irrigated sites around Faisalabad, Pakistan

Site	Wastewater available (L sec^{-1})	Wastewater use (L sec^{-1})	Area irrigated (ha)	Wastewater type	Location	Crops irrigated
Narwala Road	850	400	250	Municipal	PS-3 Chakera	Rabi season: cauliflower, spinach, wheat, sugarcane, fodder Kharif season: fodder (maize, millet, sorghum), rice
Chohar Majra	40–50	70–80	75	Municipal	PS-3 Chakera	-do-
Chak no. 279/RB	300	75	125	Industrial	Channel-3	
Sidhu Pura	70	70	50	Hospital waste	Allied Hospital WW	Wheat, fodder, rice
Islam Pura	25	25	15	Municipal	Narwala Road	Rabi season: cauliflower, spinach, wheat, sugarcane, fodder Kharif season: fodder (maize, millet, sorghum), rice
Gaoo Shala Marzipura	25	28	15	Municipal	Narwala Road	Rabi season: cauliflower, spinach, wheat, sugarcane, fodder Kharif season: fodder (maize, millet, sorghum), rice
Satiana Road	1400	250	200	Industrial	Satiana Road	Wheat, rice, sugarcane, fodder
Channel-4	1000	700	900	Industrial	Channel-4	Wheat, rice, spinach, fodder (sorghum)

surface layer led to delayed emergence of both wheat and sorghum crops. It was reported by farmers who were not irrigating crops from Channel-4 that the emergence time for wheat seedlings was 5–7 days. Conversely, for farmers who had relied on Channel-4 water for 5–16 years, the emergence of their wheat seedlings was delayed by 15 days. It is the personal observation of the authors that the growth of grain crops is rapid with wastewater, but grain yields are low. This is because overfertilization of wheat crops with N from nutrient-enriched wastewater causes excess growth and encourages weed growth and lodging, thus reducing crop yield and quality (Asano and Pettygrove 1987).

26.4.2 Economical Use of Low-quality Water

The absence of other water sources is the main reason for using wastewater. Uchkera site farmers in Faisalabad chose untreated wastewater over treated wastewater because of the higher N content and lower salinity levels of the former (Clemett and Ensink 2006). The University of Agriculture Faisalabad has 40 ha of agricultural land in Uchkera. It was observed that when canal water irrigation was replaced with wastewater irrigation, fertilizer application for wheat was reduced by 30% but the average wheat yield increased by 10%.

According to information collected from the Uchkera site farmers, fertilizer use was reduced to 1–2 bags of urea for vegetables, while groundwater-irrigating Kehala farmers also applied diammonium phosphate (DAP) and single superphosphate (SSP), as shown in Table 26.8. The cost of fertilizer was about USD 32 ha^{-1} for wastewater-reliant farmers versus about USD 130 ha^{-1} for groundwater-irrigating Kehala farmers. The farmers using canal water were considered to spend more money on utilization of fertilizers than farmers relying solely on wastewater for irrigation of crops. However, the total agricultural input costs were quite similar; that is, wastewater-using farmers spent more money on insecticides, labor hire, and land rent. On average, the Uchkera farmers achieved a gross margin of approximately

Table 26.8 Fertilizer nutrient content and market prices (PKR per kilogram or bag, and number of kilograms per bag)

Fertilizer	N (%)	P_2O_5 (%)	K_2O (%)	S (%)	Kilograms per bag	Price per bag (PKR)
Urea	46.0	–	–	–	50	1815
Diammonium phosphate (DAP)	18	46	–	–	50	4204
Single superphosphate (SSP)	–	18	–	–	50	1259
Muriate of potash (KCl)	–	–	60–62	–	50	3580
Sulfate of potash (K_2SO_4)	–	–	50	18	50	4049
NitroPhos (NP)	23	23	–	–	50	2700
Nitrogen, phosphorus, and potassium (NPK)	17	17	17	–	50	3127

USD 163 ha^{-1} and the Kehala farmers achieved a gross margin of approximately USD 66 ha^{-1} for cauliflower. Calculations for berseem also showed considerably greater gross margins for the Uchkera farmers.

26.5 Use of Wastewater Versus Canal Water

Unresolved health concerns associated with drinking water drawn from polluted water sources are certainly a problem with wastewater reuse for potable purposes. However, a properly planned and managed water reuse project can produce higher-quality finished water than unplanned reuse, as is currently common practice (Asano and Cotruvo 2004). A comparative study was conducted in Uchkera and Proka villages near wastewater treatment ponds in Faisalabad to evaluate farmers' perceptions of the social impact of wastewater use. This study showed that one village (Uchkera) used partially treated wastewater for irrigation and was nearer to the treatment ponds, whereas the other village used untreated wastewater for irrigation purposes.

A large proportion of the farmers irrigating with wastewater were of the view that wastewater offers benefits in that it is useful for crops and there is no need for fertilizer. The disadvantage of wastewater in that it is not good for the health of humans and other living organisms was a big question. The farmers' preference was to use untreated wastewater to irrigate their lands, as it has more nutrients than any other water source, as discussed above. The farmers had become habituated to the odor and dirtiness of the wastewater, and they were not aware of the religious acceptability of using wastewater for irrigation.

Women were involved in wastewater farming in Uchkera but not in Proka. Children in both villages received no education. Every farmer had his own perception about the cost and benefits of wastewater irrigation. According to most wastewater users, no problem arose from wastewater irrigation in terms of land productivity, yield per hectare, labor hire, health risks, etc. Most of the farmers were using wastewater, and untreated wastewater was preferred by most of them.

They were well aware of the limits for use of wastewater religiously but, as noted earlier, they had no choice but to use wastewater for irrigation purposes. According to farmers in the wastewater-irrigated area, use of wastewater had no effect on the health of the people working with it. According to the farmers, there were no constraints prohibiting them from using wastewater for irrigation; rather, it was productive and beneficial for them.

Wastewater irrigation should be democratized and popularized so that farmers can obtain a reliable source of water to irrigate their lands. Under these circumstances, wastewater should not be considered harmful for farmers in one form or another, because the farmers seems to be fully satisfied with it. So, it should not be banned, and Water and Sanitation Agency (WASA) officials should refrain from taking any action on it (Zafar and Akhtar 2003).

26.6 Suggestions for the Future

The various examples quoted in this chapter inspire further research for beneficial use of wastewater in agriculture.

1. *Creation of a true enabling environment*: The government should have a commitment to implement programs, water rights, and laws for promoting wastewater reuse.
2. *Public interest*: Public awareness of wastewater reuse practices can be promoted only when trust exists between the population, institutions, and operators.
3. *Decentralization for decisive outcomes*: This includes a reduced role of bureaucracy, effective municipal laws, and empowerment of local groups to promote various wastewater reuse practices.
4. *Innovation*: Interest from stakeholders and a financing infrastructure could create different positive outcomes.
5. *Special management tools*: Different financing incentives, a sludge/biosolid market, and a continuous learn-by-doing approach could result in rapid increase of wastewater use in the region.

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Management of Sodic Waters in Agriculture

27

O. P. Choudhary and M. S. Mavi

Abstract

Sustainable management of the water resources is an international priority to meet the demands of future population for food and fibre. In productive agriculture, irrigation of soils is an important component especially where rainfall is not sufficient to provide enough water for plants to complete their yield cycles. However, increasing competition for water due to rapid urbanization and industrialization is greatly affecting the water supply for irrigated agriculture in many countries. The productivity of irrigated agriculture is low in many parts of the world because of the poor quality of groundwater such as sodic water, which contains high amount of sodium. With increasing salt concentration in the water, decreasing crop yields and deterioration of soil health (physical, chemical and biological properties) have been widely observed. Thus, it is important that long-term irrigation development strategies with poor-quality sodic groundwaters are planned and implemented rationally to sustain yields without any adverse effects on soil health. Rational use of these waters by following site-specific guidelines helps to address the current and future scarcity of irrigation water. Consequently, some latest advances and technologies for utilization of poor-quality sodic waters for irrigation have been deliberated upon in this chapter.

27.1 Introduction

The global population is increasing rapidly and is expected to reach the 9.5 billion mark in 2050 (United Nations 2012). Thus, we will need approximately 60% more food to feed them (FAO 2013). Against this backdrop, the rational and sustainable

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use of good-quality water resources is a serious issue in fulfilling the growing water demands of various competitive sectors. Among various competing sectors, agriculture is the largest water user and consumes about 70% of the globally available freshwater (Singh 2015). The issue of water has become more challenging in the light of declining resource base due to urbanization, contamination and climate change impacts. Therefore, to meet the demands of future population for food and fibre, sustainable management of the water resources is an international priority. Many areas around the world with substantial parts in Australia, some countries in the Middle East, parts in North and South America and Europe, the Indian subcontinent, China and large parts of North Africa suffer from shortage of adequate supplies of good-quality water for irrigation (FAO 2008). Moreover, the increasing competition for water due to rapid urbanization and industrialization is greatly affecting the water supply for irrigated agriculture in these countries. There is growing realization that an increasing number of these countries falling in the arid and semiarid climatic zones are approaching full utilization of their surface water resources. What is left is water of marginal quality, and agriculture have to cope with this situation. Therefore, sustainable development of water resources requires that we respect the hydrologic cycle by using these marginal but renewable water resources that are not diminished over the long term by their use.

From a meagre 2.3% of total land area of the world and with only 4% of the global water resources for use, India has an enormous and challenging task of feeding 17.5% of the world's human population. Correspondingly, expansion of area under irrigation, adoption of high-yielding varieties and greater use of fertilizers during Green Revolution period in the country caused an increase in food production from just 50.8 million tonnes (Mt) in 1950–1951 to 273 Mt. in 2016–2017. Availability of assured water for irrigation not only meets the functional needs of superior genotypes but also guaranteed efficient use of plant nutrients leading to bumper yields. Thus, agriculture sector is facing competition from different sectors in India due to enhanced pace of development and rising demand for water by the oversized population. It is predicted that fall in the average size of land holdings, declining per capita availability of water, unsustainable use of good-quality water resources, deterioration of water quality, etc. will make it challenging to achieve the target of producing 494 Mt. in 2050 AD in the country.

India has one of the largest net irrigated areas in the world (63 Mha in 2009–2010), but if we look at the productivity of irrigated areas at the national level, it is only about 3 Mg ha^{-1}, since the efficacy of surface irrigation systems is about 30–40% indicating that almost 60% of the water being provided is lost at various phases in the process. The National Water Policy has clearly articulated that to fulfil the necessary food grain production of 2050, the productivity of surface water use should increase to 60% and of groundwater to 75%. In addition, the poor-quality sodic (containing high carbonates of Na) and/or saline groundwaters constitute a key portion (32–84%) of the total irrigation potential of groundwaters in various states of the country, and one fourth of the groundwater resources of the country are brackish in nature. States like Rajasthan, Haryana and Punjab located in the arid and semiarid part of the country are endowed with 84%, 66% and 42% of poor-quality groundwaters, respectively (Minhas and Gupta 1992; Sharma et al. 2010). The areas categorized by water scarcity are underlain with aquifers of poor-quality water (Minhas and Tyagi 1998). In general, sodic waters are prevalent in semiarid regions with annual rainfall of about 500–700 mm. Due to limited availability of good-quality surface water supplies in arid and semiarid regions, farmers are left with no other option except to use the groundwater of poor quality for supplemental irrigation. In addition, some areas with good-quality aquifers are threatened by contagion from nitrates and pesticide residues (Grattan and Oster 2003; Debroy and Shah 2002). Consequently, persistent and continuous use of poor-quality waters for irrigation results in build-up of soil sodicity adversely affecting its physicochemical properties (Grattan and Oster 2003) leading to lowering of crop yields (Choudhary et al. 2011b; Minhas 2012). However, if managed properly, poor-quality waters can become a vital resource for irrigation, supporting higher crop productivity. Therefore, sustainable crop production in soils receiving sodic waters should target at improving soil quality (physical, chemical and biological) through regulating and controlling build-up of sodicity in the soil.

27.2 Characterization of Irrigation Water

Quality of irrigation water is broadly characterized through electrical conductivity (EC), residual sodium carbonate (RSC) and sodium adsorption ratio (SAR). Based on their management, groundwater used in different agroecological zones can be grouped into three classes: (1) good, (2) saline and (3) sodic. Additionally, each of the poor-quality water (saline and sodic) has been further grouped into three homogenous subgroups depending on the degree of restriction (Table 27.1).

Table 27.1 Classification of poor-quality groundwater

Water quality	EC_{iw} (dS m^{-1})	SAR $(mmol^{-1})^{1/2}$	RSC (meq l^{-1})
A. Good	<2	<10	<2.5
B. Saline			
I. Marginally saline	2–4	<10	<2.5
II. Saline	>4	<10	<2.5
III. High SAR saline	>4	>10	<2.5
C. Alkali water.			
I. Marginally alkali	<4	<10	2.5–4.0
II. Alkali	<4	<10	>4.0
III. Highly alkali	Variable	>10	>4

Source: Sharma and Minhas (2003)

27.3 Chemical Composition of Sodic Irrigation Water

Water which contains high amount of dissolved carbonates and bicarbonates (CO_3^{2-} + HCO_3^-) of sodium (Na^+), greater carbonates than chlorides and sulphates and high quantity of Na^+ than Ca^{2+}+Mg^{2+} is known as sodic (United States Salinity Laboratory 1954). Normally, the soluble Na percentage is greater than 75, and the ratio of divalent cations to total cations is more than 25 for sodic waters. Alkalinity of water is expressed as (sum of cations) minus (sum of anions, other than carbonates), whereas residual alkalinity [expressed as residual sodium carbonate (RSC)] given by Eaton (1950), defined as [$HCO^-{}_3$ + CO_3^{2-}] – [Ca^{2+} + Mg^{2+}], determines the ability of irrigation water to generate alkalinity hazard in the soil and is being used as an index of water suitability for irrigation of crops in the soil testing laboratories of India. In general, waters having high RSC test low in EC, whereas saline-sodic waters test high in RSC, SAR and EC. Irrigation waters having RSC < 2.5, 2.5–5 and > 5 meq L^{-1} are considered to be safe, marginal and unsafe, respectively (Bhumbla et al. 1972). Additional parameters for testing the potential of irrigation waters to generate alkalinity or sodicity hazards are sodium adsorption ratio [SAR = (Na)/√(Ca + Mg)/2], concentrations expressed in mmolc L^{-1} and new adjusted SAR (adj.RNa) defined as Na/√[(Ca_x + Mg)/2, where Ca_x represents the Ca in applied water modified due to salinity (ionic strength) and HCO_3^-/Ca^{2+} ratio (Ayers and Westcot 1985). Furthermore, the level of Na saturation in soil regulates the potential of growing various crops and sustaining greater crop production efficiency under sodic water irrigation. Thus, ability to predict the extent of ESP build-up in soil under long-term sodic water irrigation of diverse cropping schemes assumes significance for selection of crops and planning crop-water-soil management systems. Consequently, data of long-term field experiments (Bajwa and Josan 1989a,b; Minhas and Bajwa 2001) show that adj.RNa can act as a useful index to predict the ESP build-up in soil under sodic irrigated millet/maize-wheat rotation, predominantly because it does not require the usage of any empirical constant. But for rice-based cropping system, 2.6 times adj.RNa looks to be reliable. As concept of adj. RNa uses Ca_x, it offers a superior insight into the change in Ca^{2+} concentration in soil solution due to release of calcium from soil minerals or its retention/precipitation in soil. Under the monsoonal climate, the development of sodicity upon irrigation with sodic waters largely depends upon equilibrium between precipitation of calcite and other salts during irrigation to crops (especially in winter season) and their dissolution with rainwater. Sodicity (ESP) build-up could be reasonably predicted (Minhas and Sharma 2006) from the annual amounts of sodic waters applied (D_{iw}), the rainfall (D_{rw}) at the site and the evapotranspiration demands of the crops grown in sequence.

$$\mathrm{ESP} = (\mathrm{Diw}/\mathrm{Drw})\left(\surd(1 + \mathrm{Drw}/\mathrm{ET})\ (\mathrm{adj.RNa})\right).$$

Thus based upon the ion chemistry of water (RNa), parameters like D_{iw}, D_{rw} and ET of crops and their sodicity tolerance and cropping patterns can be appropriately adjusted.

27.4 Hazardous Impacts of High Sodium on Soil Exchange Sites

Soils can be naturally sodic or can become sodic by the application of irrigation water with high SAR and RSC. Some of the key elements responsible for build-up of salts in soil are geology, climate, topography and human activities. Large amounts of salts can be transported to surface or groundwater through geological formations consisting of salt-rich sediments. Geomorphology has considerable effect on salt levels, increasing them within closed basin or lowland areas, where groundwater rises due to poor drainage system. In addition, climatic factors like low precipitation and high evaporation can increase the concentration of salts in soils, surface and groundwater causing sodicity. Some human-induced factors responsible for high sodicity levels in the soil are over-irrigation with water containing high levels of salts and improper use of land. Therefore, sodic soils, due to poor structure, are susceptible to erosion and loss of organic matter causing poor plant growth and reduced farm production and income (Sumner et al. 1998).

Salt accumulation in soil depends on soil texture which influences hydraulic properties of the soil. High sodium concentration on the soil exchange sites with low salt concentrations in the soil solution leads to dispersion and degradation of soil structure. Swelling and dispersion of clay particles after wetting are the prime causes for the weakening of the soil structure (Rengasamy et al. 1984). Soil clay particles have a negative charge and thus attract cations and build a zone of positive cations around clay particles known as ‘diffuse double layer’. Within this diffuse double layer, the concentration of cations is higher near the surface of clay particles and decreases with distance. When the diffuse double layer is thickened by large hydrated ions like Na^+ or due to electrostatic repulsion, the clay particles disperse (Shainberg 1992). These clay particles move through the soil profile clogging pore spaces and thus reducing water infiltration and nutrient movement within the soil. Consequently, soils under long-term sodic water irrigation are very wet immediately after rain or irrigation and become very dry when water dries out through evaporation within a few days. In addition, the solubility of sodium and boron increases due to high pH and leads to ion toxicity along with waterlogging (Naidu and Rengasamy 1993). Therefore, lower structural stability in the sodic soils may cause soil surface hardening by seal and crust formation thereby causing poor root development and plant growth with greater danger of soil erosion (Sumner et al. 1998).

Additionally, low ESP or SAR soils can also display sodicity when the electrolyte amount is below the critical flocculation concentration (CFC) (Quirk and Schofield 1955). Similarly, a study by Rengasamy et al. (1984) indicated that at $EC_{1:5}$ greater than 0.6 dS m^{-1}, red-brown earths of South Australia remained flocculated regardless of the percentage of sodium on the soil exchange complex (Fig. 27.1). Thus, depending on the degree of sodium saturation, soil permeability and structure can be maintained by application of water at the appropriate electrolyte level. Although high concentration of Na^+ in soil causes dispersion, complementary divalent cations like Ca^{2+} have the potential to promote flocculation (Keren and Ben-Hur 2003). However, further investigations are required in a range of soils irrigated with sodic water with varying salinity levels.

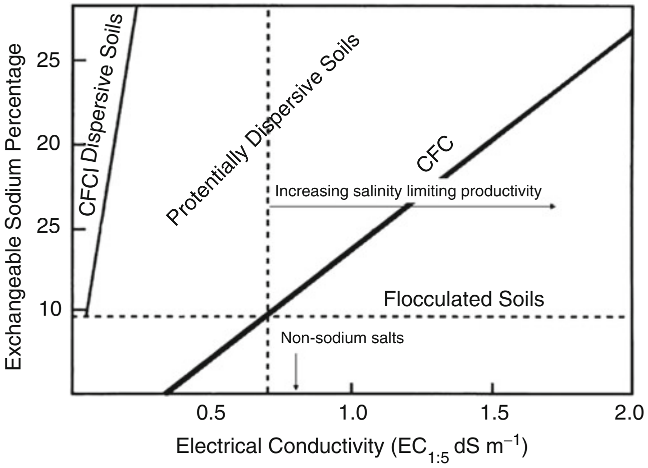


Fig. 27.1 Association between ESP, EC and dispersion (modified from Rengasamy et al. 1984) CFC, critical flocculation concentration

27.5 Strategies Managing Sodic Waters for Sustainable Crop Productivity

Sodic water remains a valuable resource notwithstanding the difficulties associated with their use for irrigating crops and the potential for reduced soil permeability (Murtaza et al. 2009). Accordingly, if the challenges of satisfying the global food demand are to be fulfilled, it is vital that the sodic groundwaters are used properly to sustain crop productivity. Options to manage and sustain crop production in a salt-affected environment are (i) modifying the environment to suit the plant and (ii) modifying the plant to suit the environment. Both these approaches have been used, either individually or in combination, but the former has been used more extensively because it facilitates alternative production inputs. For sustainable crop production, practical options for safe use of poor-quality waters should aim at controlling build-up of sodicity apart from reducing its adverse effect on physico-chemical properties of soils. This approach will not only add an additional water resource in arid and semiarid areas but can also minimize the rising water table problem in these regions. To sustain crop productivity using sodic waters, strategies include selection of suitable cultivars, managing irrigation strategies, chemical/organic amendments and fertility management. No single management practice is sufficient to rectify sodicity of irrigated soils alone; rather a combination of practices is prerequisite. Different management options are described separately in the following sections.

27.6 Laser Levelling of the Land and Rainwater Harvesting

For managing the land irrigated with sodic water, land levelling and provision of 30–40 cm high strong bunds for capturing and retaining rainwater are the essential prerequisites. In addition, by ploughing the field in between rains, the highly erodible sodic soil on the surface can be protected against beating action of raindrops. Besides increasing intake of rainwater, this practice helps in controlling the unproductive losses of water through weeds and evaporation. Moreover, these practices also promote uniform salt leaching and self-reclamation through the rain-induced dissolution of soil calcium carbonate.

27.7 Selection of Suitable Crops and Varieties

The main aim is to select suitable crops and cultivars which can give higher productivity and monetary returns under different levels of soil Na saturation. Since crops and their cultivars differ in tolerance to soil sodicity/alkalinity (Mass and Hoffman 1977; Ayers and Westcot 1985), it may form the basis of selection of crops for growing on soils irrigated with water varying in sodicity levels. The upper permissible ESP limits for various crops were proposed by Gupta and Abrol (1990) (Table 27.2). Most crops show varying levels of tolerance to increasing levels of ESP in soil at different growth stages like germination, early seedling development and reproductive and grain formation.

Generally, crop grown in the preceding season greatly affects the production and productivity of the crop in the following season. In a monsoonal climate, crops that favour higher retention and in situ conservation of salt-free rainwater cause less development of sodicity in the soil profile at the end of the season, thus providing a healthier environment for the succeeding crop (Tyagi 2003). Sharma et al. (2001) through a 6-year study showed that the productivity of the rice-wheat system was higher than the sorghum-wheat and cotton-wheat systems when irrigated with sodic water. Similarly, results of a field study with sequential application of freshwater and

Table 27.2 Sensitivity of crops to a range of ESP levels

ESP range[a]	Crops
10–15	Safflower, peas, lentil, pigeon pea, urd bean, banana
16–20	Bengal gram, soya bean, papaya, maize, citrus
20–25	Groundnut, cowpeas, onion, pearl millet, guava, bael, grapes
25–30	Linseed, garlic, guar, palmarosa, lemongrass, sorghum, cotton
30–50	Mustard, wheat, sunflower, *ber, karonda*, *phalsa*, vetiver, sorghum, *berseem, senji*
50–60	Barley, sesbania, para grass, Rhodes grass
60–71	Rice, sugar beet, Karnal grass

[a] Threshold ESP; Gupta and Abrol (1990)

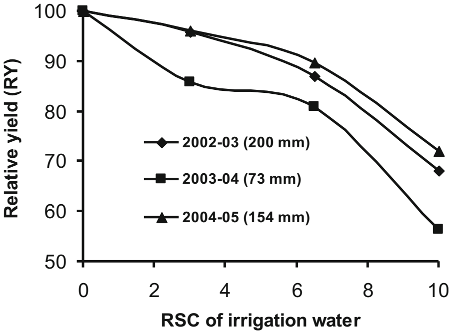
alkaline water (FW:AW) showed that the equivalent yield of basmati rice was 7 t ha^{-1} as compared with only 4.3 t ha^{-1} for non-basmati rice (Sharma et al. 2001). Greater monetary returns led to its cultivation in a larger area in Haryana, even though its physical water productivity was only half of non-basmati rice. Similar trends were reported with mustard, which replaced wheat because of its high salt tolerance with requirement of only one or two post-sowing turns of irrigation compared with four or five turns of irrigation for wheat (Tyagi 2003).

Rice and wheat are the crops most commonly recommended for growing in salt-affected soils during reclamation process as both these crops can tolerate higher levels of salinity and sodicity. However, rice is not recommended to be grown with saline and sodic waters as rice and other high water-requiring crops need large number of irrigations (24–28) that can appreciably increase salt load and Na build-up in the soils and hasten the degradation of the soils. So under poor-quality water irrigation, low water-requiring crops that are tolerant or semi-tolerant to the salts should be raised.

Salt-tolerant cultivars of rice (CSR 23, CSR 27, CSR 36) and a basmati cultivar (CSR 30), wheat (KRL1–4, KRL19, KRL 210) and mustard (CS 52, CS 54) have been developed by ICAR-Central Soil Salinity Research Institute, Karnal. All these tolerate high levels of salinity up to ECe of 7–10 dS m^{-1} and high levels of alkalinity (pH_2 9.3–10). At Kanpur, screening of rice, wheat and mustard cultivars was carried out under sodic condition (soil pH, 9.3; ESP, 45.3) (Annual Report, AICRP SAS&USW, 2016–2017). In case of rice, the maximum yield 43.1 q (1q = 100 kg) ha^{-1} of rice was recorded from variety CSR 36 followed by CSR 23 (40.7 q ha^{-1}) and CSR 27 (38.2 q ha^{-1}). For wheat, the maximum yield 35.4 q ha^{-1} of wheat was recorded from variety KRL 210 followed by KRL 213 (34.3 q ha^{-1}) and PBW 343 (32.8 q ha^{-1}), while the minimum yield 26.9 q ha^{-1} was obtained from WH-147. Among different varieties of mustard screened, the maximum yield 16.20 q ha^{-1} of mustard was recorded from variety CS 56 followed by CS 54 (14.6 q ha^{-1}) and CS 52 (13.3 q ha^{-1}) with the minimum yield of 10.46 q ha^{-1} from Urvasi. However, it is pertinent to mention that all these screening studies were conducted on a native sodic soil irrigated with good-quality water.

Choudhary et al. (1996a, b) reported that tolerant wheat genotype had penetrative root system and higher spike density than the sensitive ones. Crop cultivars with varying yield potential even under higher levels of soil sodicity should be favoured over those having lesser yield potential. A classic example is that of high-yielding wheat cultivar PBW-343 that can produce high grain yield and quality without any significant loss even with irrigation waters having RSC up to 6.5 me L^{-1} (Choudhary et al. 2007, 2012a). In addition, crops having low irrigation requirement should be preferred (Minhas and Gupta 1992). A greater reduction in productivity of sodic-irrigated wheat grown after high irrigation-requiring rice crop as compared to low irrigation-requiring millet and cotton crops have been reported under long-term experiments. Since build-up of ESP under sodic water irrigation is higher in the surface soil and it decreases with depth (Bajwa and Josan 1989a, b, c; Choudhary et al. 2004), thus more data needs to be generated concerning tolerance and production efficiency of various crops (varying in rooting behaviour) and their cultivars in

Fig. 27.2 Influence of rainfall on the response of 'PBW 343' to RSC (me L^{-1}) of irrigation water in different years. (Source: Choudhary et al. 2007)



soils irrigated with sodic water. The response of wheat cultivar PBW 343 to sodicity (RSC) of irrigation water was influenced by the number of irrigations and amount of annual rainfall (Fig. 27.2). Subsequently, Choudhary et al. (2012a) concluded that cultivar PBW 343 should be preferred over other wheat cultivars (PBW 550 and PBW 502) to obtain acceptable yield levels without any loss in grain quality in soils irrigated with sodic waters containing RSC > 5 me L^{-1}. Soil-plant system may develop nutritional imbalance due to stark decrease in Ca concentration (below 2 meq L^{-1}) in soil solution (Rhoades et al. 1992) with increase in sodicity and soil Na saturation. Tolerance of crop plants to sodicity is also governed by the capacity of plant roots to eliminate Na and absorb nutritionally sufficient amounts of Ca (otherwise deficient under sodic soil environment). Crops having higher tolerance to soil Na saturation have also been reported to maintain relatively higher Ca/Na and lower Na/K ratios in shoots (Bajwa 1982; Choudhary et al. 1996b) by restricting Na absorption (Gill and Qadir 1998).

Long-term irrigation with sodic waters (having RSC of 5, 10 and 15 me L^{-1}) adversely affected growth and yield of three cotton cultivars (Choudhary et al. 2001). Compared with the canal water (CW) treatment, relative seed cotton yield under ESP of 56.2 was 69% in F-846, 49% in LD-327 and only 29% in F-505. Cultivar F-846 produced larger bolls than the other two cultivars under irrigation with higher RSC waters. The harmful effects on fibre quality (2.5% span length and bundle strength) observed in F-505 and LD-327 at an ESP of 56.2 in the soil were not observed in case of F-846. Recently, among Bt cotton hybrids, RCH 134 was observed to perform better than MRC 6301 and MRC 6304 (Choudhary et al. 2012b).

Over the past four decades, concerted hard work have resulted in the development of promising salt-tolerant varieties in rice, wheat and mustard. However, there is a growing realization for the development of multiple stress-tolerant crop genotypes on priority basis by integrating molecular and genomics tools with conventional breeding approaches because exclusive focus on breeding for salt tolerance would no longer work (Sharma and Singh 2015). In India, the research on development of salt-tolerant rice varieties started in the 1940s with the release of cultivars such as Pokkali and Jhona 359 established through selection from the locally adapted landraces under coastal saline-sodic and inland saline-sodic soil conditions, respectively. Since 1960s onwards, systematic breeding efforts resulted in the development of many promising profitable cultivars (Singh et al. 2010). However, only a few have become popular among the farmers. The major reasons behind limited adoption by the farmers are low level of salt tolerance relative to the locally adapted landraces and poor grain quality (Singh et al. 2010). Nowadays, greater emphasis is given on quantitative trait loci (QTL) mapping and marker-assisted breeding for introgression of markers tightly linked to the submergence tolerance gene (SUB1) and QTL for sodicity tolerance at the seedling stage (qSAL-TOL) in the background of high-yielding cultivars (Singh et al. 2010).

27.8 Use of Amendments to Alleviate Impacts of Sodic Irrigation Water

27.8.1 Chemical Amendments

The application of chemical amendments can be very helpful in alleviating the harmful effects of sodic water irrigation on soil physico-chemical properties by providing soluble calcium to replace exchangeable sodium adsorbed on clay surfaces. There are two main types of amendments: those that add calcium directly to the soil and those that dissolve calcium from calcium carbonate ($CaCO_3$) already present in the soil.

Calcium amendments include gypsum (hydrated calcium sulphate) and calcium chloride. Gypsum is moderately soluble in water and is the most commonly used chemical amendment. Calcium chloride is highly water soluble and fast acting, but it generally is too expensive. Acid-forming, or acidic, amendments include sulphuric acid, elemental sulphur and pyrite. Sulphuric acid reacts immediately with the calcium carbonate in the soil to release soluble calcium for exchange with sodium. Elemental sulphur and pyrite must be oxidized by soil bacteria and react with water to form sulfuric acid. The formation of sizeable amounts of sulphuric acid from these materials may take several months. Calcium carbonate must be present in the soil when acid or acid-forming amendments are added (Choudhary 2017).

Choice of amendment is made mainly on the basis of the cost of the soluble calcium supplied directly or indirectly by the amendment, the speed of the reaction of the amendment in soil and ease of its application (Table 27.3).

Table 27.3 Compared with gypsum relative quantities of various other chemical amendments

Amendment	Tonnes equivalent to 1 tonne of gypsum
Sulphur	0.18
Lime sulphur	0.75
Sulphuric acid	0.57
Iron sulphates ($FeSO_4.7H_2O$)	1.62
Aluminium sulphate $Al_2(SO_4)_3.18H_2O$)	1.27
Limestone ($CaCO_3$)	0.58

Source: Choudhary (2017)

Cheap acidic industrial wastes like press mud (a waste product from sugar factories) can be profitably used for sodic soil improvement. It contains either lime or some gypsum depending on whether the sugar factory is adopting carbonation or sulphitation process for the clarification of juice. It also contains variable quantities of organic matter.

The need for gypsum application for ameliorating the sodic irrigation effects is of the recurring nature in contrast to reclamation of an alkali soil. Gypsum application has been recommended earlier once RSC of irrigation water exceeded 2.5 me L^{-1}. But, subsequent research has shown that other factors like the extent of the deterioration of the soil properties, cropping intensity and water requirements of the crops will be the deciding factors governing the amount of gypsum required. In addition, the amount and type of chemical amendments required to reclaim a sodic environment will also depend on crop tolerance to sodicity and economic condition of the farmers. Data has shown that sustainable yields of rice and wheat irrigated with sodic water (RSC > 4) are possible with occasional application of gypsum and FYM. Bajwa and Josan (1989a) reported that gypsum applied with each irrigation vis-a-vis applied on cumulative basis were equally effective for wheat crop. However, in case of rice, gypsum applied with each irrigation particularly under high RSC water showed an edge over its cumulative application.

In North-Western India, Pal and Poonia (1979) reported that gypsum bed technique using gypsum fragments or rock gypsum applied in water courses/beds as advocated by Kemper et al. (1975) was found to be effective and also caused reduction in cost of its application. In fact, the dissolution of gypsum is affected by factors such as size of gypsum fragments (determine surface area), flow rate (influence contact time) and total salt content and chemical composition of water (Kemper et al. 1975; Singh et al. 1986). However, calcium picked up by the passing well waters increases in range from 3 to 5 meq L^{-1}, but it seldom exceeds 8 meq L^{-1} (Singh et al. 1986). Usually 30–60 cm in height of gypsum bed is recommended to bring RSC within permissible limits. Choudhary et al. (2004) through a long-term study reported that the beneficial effect of gypsum was more prominent in increasing cane and sugar yield under sodic (30%) than saline-sodic water irrigation (13%).

27.8.2 Organic Amendments

Properties of sodic soil are generally improved by additions of organic materials through mobilization of Ca^{2+} from $CaCO_3$. Choudhary et al. (2011a) reported that repeated irrigation with sodic water (SW) caused gradual increase in exchangeable sodium percentage (ESP) and soil pH in a calcareous soil. Significant adverse effects of sodic water irrigation were observed after 7–9 years in rice and wheat grain yields, whereas harmful effects were not marked during initial years (Fig. 27.3). Overwhelmingly, the results confirmed that in calcareous soils, mobilization of Ca^{2+} from $CaCO_3$ during decomposition of organic materials [such as farmyard manure

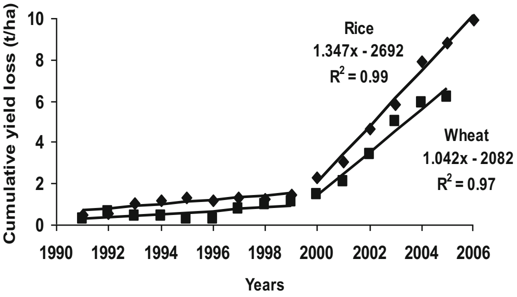


Fig. 27.3 Comparative cumulative yield loss over the years in sodic water irrigation than good-quality canal water. (Source: Choudhary et al. 2011a)

(FYM), *Sesbania aculeata*], the requirement of gypsum for controlling the detrimental effects of sodic water irrigation, can be reduced in rice-wheat cropping system.

The application of wheat straw before rice transplanting was less effective than FYM and GM in increasing rice yield over SW-alone treatment but was at par with GM in its residual effect on the following wheat yield.

In sugarcane, FYM showed better results under saline-sodic (38%) than SW irrigation (23%) (Choudhary et al. 2004). Relative to CW treatment, no decline in yield (12.3 Mg ha^{-1}) up to an ESP of 12 was observed. This level of ESP can be maintained under long-term SW irrigation through application of gypsum and FYM. Sugar yield under FYM treatment (10.8 Mg ha^{-1}) was on par with gypsum plus FYM treatment but was significantly higher than the sole gypsum treatment (9.0 Mg ha^{-1}) under saline-sodic irrigation. It was concluded that better cane and sugar yields can be obtained by application of gypsum/FYM or both under sodic and only FYM under saline-sodic water irrigated soils. In addition, soil physico-chemical and biological problems like reduced microbial activity, low cation exchange capacity, poor aggregation and reduced water and nutrient holding capacity arise due to scarcity of organic matter in the salt-affected soils (Liang et al. 2005). Of late, biochar, a carbon-rich, porous product formed due to thermochemical conversion of biomass at temperature around 350–700 °C under low oxygen conditions (Amonette and Joseph 2009), has received immense global importance as an organic amendment in the field of sustainable agricultural waste management. Apart from its C stabilizing effects, biochar has been shown to increase microbial activity and biomass due to the presence of labile C fractions (Singh and Mavi 2018; Mavi et al. 2018). Enhanced soil available nutrients, adsorption of toxic compounds and improved soil pH status all could be an explanation for the positive impacts of biochar application on soil flora (Lehmann et al. 2011). Besides, biochar improves soil structure due to its beneficial effects on pore and particle size distribution, bulk density and water holding capacity of the soils (Kammann et al. 2011; Karhu et al. 2011). Such properties of biochar support its potential use as a soil amendment in reclamation of salt-affected soils. Consequently, Singh et al. (2018) reported that application of higher rates of rice-residue biochar (2–4%) helped microbial community to override the negative effects of elevated salt concentrations because of release of labile substrates from biochar and partially due to its ability to sorb salts temporarily from the soil. Similarly, Singh and Cowie (2014) and Chahal et al. (2017) also indicated that biochar supports growth and activity of microorganisms, possibly by providing intrinsic labile organic components for microbial proliferation and, therefore, could be utilized as a potential amendment for ameliorating the salt-affected soils.

Besides this, focus on amelioration strategy involving microbial-assisted/microbial-mediated calcite dissolution to reduce soil and water sodicity is gaining importance (Sulu-Gambari 2011; Tamilselvi et al. 2016). Tamilselvi et al. (2016) reported a calcite dissolving *Brevibacterium* sp. SOTI06 with a potential to dissolute 18% calcite with a simultaneous release of Ca^{2+} ions under in vitro conditions. However, further long-term research is warranted in this regard.

27.8.3 Role of Organic Amendments in Reclaiming Sodic Subsoil

Subsoil sodicity acts as a key limiting factor in crop production in many soils of the world. A survey on subsoil properties in duplex soils in the high rainfall zone of South-West Victoria (Australia) reported that the clay subsoils were largely sodic with exchangeable sodium percentages fluctuating between 14% and 22%. Growth of plant roots in these sodic subsoil layers is strictly restricted, and thus crops were unable to extract the deep subsoil water which tended to remain continuously moist below 50–60 cm.

For ameliorating dense clay sodic subsoil, one of the management options is the deep incorporation of organic amendment into the subsoil layers. Gill et al. (2008) studied the effects of deep incorporation of organic and inorganic amendments in 30–40 cm layer on soil properties and grain yield of wheat in Sodosol with dense sodic subsoil in a high rainfall region (long-term average annual rainfall 576 mm) of Victoria (Australia). Deep ripping alone or along with gypsum did not significantly affect wheat grain yields. On the other hand, application of organic amendments doubled biomass production and increased grain yield by 1.7 times. Organic amendment applied plots yielded 60% more grains per unit area than the untreated control. The crop removed over 50 mm more water from below 40 cm soil in plots treated with organic amendment than the untreated control. Nitrogen uptake was almost doubled in the plots treated with organic material than the untreated control. The improved yield due to addition of amendments caused an increase in plant available water in the hostile subsoil, extended greenness of leaves and supply of nitrogen and other nutrients. They proposed that a series of processes as outlined in Fig. 27.4 contributed to the outcome.

27.9 Phytoremediation of Soils Irrigated with Sodic Water

An effective low-cost intervention for resource-poor farmers is the phytoremediation (vegetative and biological) of sodic and saline-sodic soils. Phytoremediation comprises cultivation of certain tolerant plant species whose root action helps

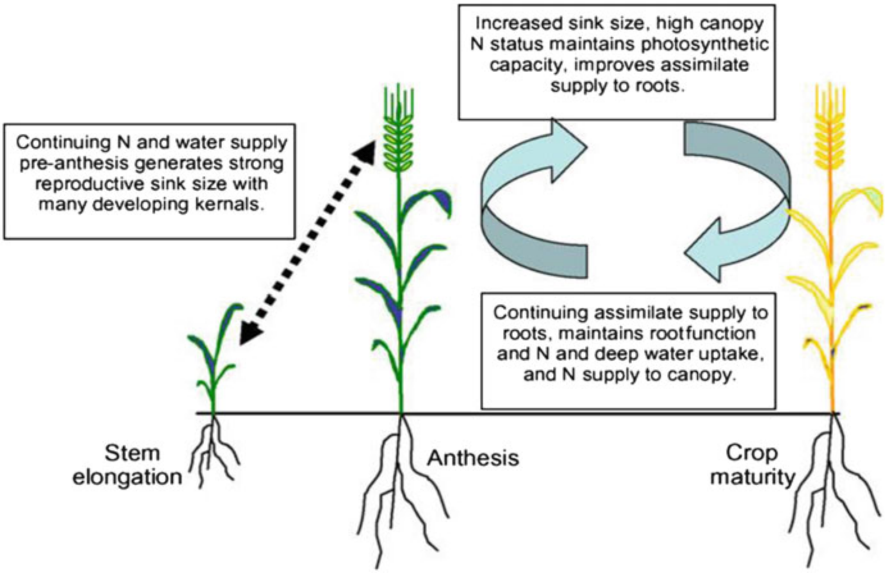


Fig. 27.4 Processes proposed by Gill et al. (2008) that caused delayed senescence where organic amendments were incorporated into the sodic subsoil

dissolve the native $CaCO_3$ for an effective $Na^+ - Ca^{2+}$ exchange at the soil exchange sites. Many researchers have reported phytoremediation to be an effective amelioration strategy against the use of chemical amendments especially for calcareous sodic soils with comparable performance.

27.9.1 Mechanisms and Processes Driving Phytoremediation

Phytoremediation of calcareous sodic soils ($\mathrm{Phyto_{Sodic}}$) is a strategy of increasing the dissolution rate of calcite through processes at the soil-root interface causing greater levels of Ca^{2+} in soil solution (Qadir et al. 2007). It is a function of the given factors:

$$\mathrm{Phyto_{Sodic}} = \mathrm{RP_{CO2}} + \mathrm{R_H}^+ + \mathrm{R_{Phy}} + \mathrm{S_{Na}}^+$$

where $\mathrm{RP_{CO2}}$ refers to increased partial pressure of CO_2 within the root zone, $\mathrm{R_H}^+$ is enhanced proton (H^+) released in the root zone, $\mathrm{R_{Phy}}$ addresses physical effects of roots in improving soil aggregation and hydraulic properties of the root zone and $\mathrm{S_{Na}}^+$ represents Na^+ content of shoot, which is removed through harvest of the aerial plant portion. All these factors collectively lead to soil amelioration, provided drainage is adequate and sufficient leaching occurs.

Many crops have been tested as phytoremediation strategy in these studies including alfalfa, Karnal grass, tall wheat grass, barley and cotton. However, degree and depth of soil reclamation varied with different plant species. Most studies demonstrated reduction in soil sodicity levels while using irrigation waters containing low sodicity.

The advantages of this approach are:

(i) Purchase of chemical amendments is not required.
(ii) Additional financial benefits from plants grown for amelioration.
(iii) Porosity and soil aggregate stability is improved as a result of root activity, with subsequent enhancement in soil hydraulic properties.
(iv) When leguminous crops are used, plant nutrient availability in the soil is enhanced due to addition of organic matter by belowground plant material as well as N fixation.
(v) Especially in case of deep-rooted crops, the zone of amelioration is more uniform and deeper.
(vi) In the post-amelioration soil, carbon sequestration is an additional advantage.

Even though plant-assisted amelioration strategy is a promising option to ameliorate sodic soils, it is pertinent to mention that phytoremediation is a very slow process and takes lot of time before any unproductive land is ameliorated. Therefore, farmers of the intensively cultivated state like Punjab may not be very much inclined to this option compared to faster processes like chemical amendment. Phytoremediation could be more suitable in arid and semiarid areas of Pakistan where large part of the land is barren and productivity levels are comparatively lower.

27.10 Agroforestry as a Strategy to Ameliorate Soils Degraded Due to Sodicity

Studies conducted to observe the role of afforestation to ameliorate salt-affected soils indicate that decomposition of large amount of litter shed by tree during its growth period releases several weak acids (humic and fumic) to lower down the soil pH and EC. It was observed that the litter production after 10 years of tree growth by *Prosopis juliflora*, *Casuarina equisetifolia, Acacia nilotica*, *Terminalia arjuna and Pongamia pinnata* caused a significant improvement in the physical properties (like bulk density, porosity and infiltration rate) of the sodic soil (Singh et al. 2008, 2011).

Similarly, Singh and Gill (1992) reported that forest growth over 40 years reclaimed the salt-affected soil in many properties. Several soil characteristics of both forest and non-forested sodic soils were measured by Singh and Goel (2012) to analyse the degree of reclamation in the degraded soil. Microbial biomass carbon (MBC), nitrogen (MBN) and phosphorus (MBP) decreased significantly from the surface to a depth of 45 cm (Table 27.4). The mean MBC up to 0–45 cm depth was 131 μg g^{-1} in forested soil which was approximately three times greater than non-forested sodic soils.

Table 27.4 Biological properties of forested (F) and non-forested sodic (C) soils (μg g^{-1})

		Depth (cm)				
		0–15	15–30	30–45		
Character	State	Mean ± SD	Mean ± SD	Mean ± SD	Mean	$LSD_{0·05}$
MBC	F	285.0 ± 87.7	55.0 ± 33.2	33.3 ± 13.6	124.6 ± 44.79	15.0
	C	89.0 ± 6.7	32.0 ± 9.2	19.7 ± 4.6	47.0 ± 2.3	
MBN	F	53.0 ± 3.1	20.0 ± 6.0	10.2 ± 0.8	27.5 ± 2.6	4.4
	C	14.0 ± 3.8	8.3 ± 0.2	5.0 ± 0.8	9.2 ± 2.0	
MBP	F	26.0 ± 7.0	15.6 ± 4.4	10.7 ± 2.3	17.4 ± 2.4	7.0
	C	10.0 ± 3.8	5.6 ± 0.8	4.2 ± 1.2	6.5 ± 1.7	

Source: Singh and Goel (2012)

27.11 Fertility Management

Excess soluble salts in the soil solution, high pH, excessive exchangeable Na and adverse soil physical properties due to the long-term use of sodic waters influence the transformations and availability of native and applied fertilizer nutrients.

27.11.1 Nitrogen

In the presence of Na and salts, N use efficiency usually declines. The slow N transformations were due to reduction in microbial population with increase in ECe and pH. It has been have shown that nitrification is more sensitive to salinity than ammonification process, resulting in accumulation of NH_3 and nitrites (Pathak and Rao 1998). Urea hydrolysis became slower with increase in salinity/sodicity (Singh and Bajwa 1986). Ammonia volatilization is a major loss mechanism in saline-sodic water irrigated soils. It increased with increase in EC, RSC and SAR of irrigation waters. Losses as high as 37% and 40% were observed under soils receiving irrigation waters having 15 me L^{-1} RSC and 4 dS m^{-1} EC, respectively. To decrease losses of N and increase N use efficiency, splitting of fertilizer N so as to match crop demands at different growth stages, deep incorporation, slow-release N fertilizers and application of urease inhibitors have been found to be useful. Generally, application of higher dose (25–50%) of N than that for normal soils constitutes one strategy to overcome the adverse effects of salinity. But it has been observed that when salinity/sodicity is not a limiting factor, applied N fertilizers will increase the yields of crop proportionally more than when the salinity becomes a limiting factor. Dhir et al. (1977) reported maximum response fertilizer N applied to wheat crop at EC_{iw} 4 dS m^{-1}; it decreased around ECiw 8 dS m^{-1}, and there was no response at EC_{iw} 16 dS m^{-1}. For improving N use efficiency, a better strategy seems to be to substitute a part of inorganic fertilizer requirements through organic materials. Addition of FYM will help in improving the physical properties of soil, increasing moisture retention and decreasing nutrient losses. Following the application of N through inorganic fertilizer sources, a large pool of NH_4^+ liable to be lost through volatilization is bound with organic forms temporarily binding the ammoniacal N and subsequently releasing the organically bound N to crops during its growing season. The composition of salts in alkali environment influences the choice of fertilizers for crops. Bajwa and Singh (1992) observed that under flooded alkaline soil conditions, urea, ammonium sulphate and ammonium chloride placed in reduced zone produced similar rice yields, whereas nitrate-containing fertilizers were appreciably inferior. In case of wheat, effectiveness of fertilizers containing both NH_4^+-N and NO_3^--N was similar. The reclamation of sodic soils has been found to decrease losses of volatile ammonia (Bajwa and Singh 1992).

27.11.2 Phosphorus

High alkalinity in soil and water results in the conversion of native insoluble Ca-P to soluble Na-P. Therefore water-soluble P increases with soil pH in all the major benchmark series of alkali soils of the Indo-Gangetic plains. Thus during early stages of reclamation and under conditions where farmers add lower doses of chemical amendment gypsum, the soils release sufficient P in soil solution for use by plants (Chhabra 1985). When sodic soils were reclaimed using amendments and growing rice under submerged conditions, Olsen's extractable P of surface soils decreased due to its movement to lower layers and uptake by the crop (Swarup 1998). Decrease in ESP and pH of the soil upon reclamation leads to increase in sorption of soluble P.

The critical value below which crop responds to applied P varies greatly with the nature of the crop, stage of soil reclamation and initial soil test value. Rice and wheat crops grown on freshly reclaimed alkali soils (i.e. during initial 3–5 years) have not been found to respond to the application of phosphatic fertilizers. But when this surface soil layer gets depleted, rice crop having shallow root system starts responding to P fertilization. Wheat plants with a relatively deeper root system can absorb P from the lower layers also and do not respond to applied P for 3 to 5 years. Further, considering contributions from the sub-surface soil, lower doses of P should be enough to get optimum yields of rice crop in alkali soils. All phosphatic fertilizers containing water-soluble P are more effective than those containing wholly or partially water-insoluble P. Single superphosphate (SSP) is a better source of P than other phosphatic fertilizers as it contains some amount of calcium sulphate (Swarup 1998).

27.11.3 Potassium

In sodic soils high contents of Na and deficient amounts of Ca result in decreased uptake of K by the plants. Potassium content in plants had been found to be related with K/Na ratio and not with the absolute concentration of K (Chhabra 1985). Alkali soils of Indo-Gangetic plains generally contain very high amounts of available K due to the presence of illitic clay mineral (Swarup and Chhillar 1986). Application of K fertilizers in these soils neither increased K contents of plants nor yields of rice and wheat. Nevertheless, crop response to K nutrition depends upon the cultivar and its capacity to selectively absorb K under strong antagonistic effect of Na. Joshi et al. (1980) reported that tolerant wheat cultivars accumulated more K and less Na than the sensitive varieties and suggested that Na/K ratio may be used as an index for predicting varietal sensitivity to high soil Na saturation.

Results of long-term field trials conducted on alkali soils indicate that in the treatment receiving fertilizer K, the contribution from nonexchangeable K was lower as compared to without K fertilization (control, 100% N and 100% NP). This contribution was more in plots receiving N and P fertilizers as compared with control (Yaduvanshi and Swarup 2005). This may be due to better growth of the plants and thus higher removal of soil K from treatments receiving both NP and N as compared with control. The contribution of the nonexchangeable K towards total potassium removal was about 94.9% in the absence of applied K which decreased to 69.9% with use of K. It was further decreased to about 50% with combined use of K with organic manures (Yaduvanshi 2001). Singh and Sharma (2001) observed that the nitrogen use efficiency of 120 kg N ha^{-1} without potassium application was 29.8, 21.4 and 21.7 kg in the year 1992–1993, 1993–1994 and 1994–1995. But when 50 kg K ha^{-1} was applied along with the same dose of N, nitrogen use efficiency increased to 33.1, 26.5 and 27.5 kg in the respective years.

27.11.4 Micronutrients

Irrigation with sodic water regularly over a period of time decreases the availability of micronutrients such as Zn and Fe resulting in the deficiency of these nutrients, particularly so in arid and semiarid regions where soils are generally calcareous. Besides being poor in available Zn, the use efficiency and recovery of applied Zn is further adversely affected due to 85–90 per cent fixation of applied Zn (Chauhan et al. 1999). The solubility of Zn in sodic soils/sodic-water irrigated soils is controlled by the solubility of $Zn(OH)_2$ and $ZnCO_3$, which are the immediate reaction products. Sadana and Bajwa (1985) found that addition of FYM, pyrites and gypsum shortened the period of predominant existence of $Zn(OH)_2$-Zn^{2+} (aq.) system which increased the solubility and thereby availability of zinc in sodic soils. Likewise, Bajwa et al. (1992) observed that sodic water irrigations for 9 years caused significant decline in DTPA-extractable micronutrients. This decline in yield was more pronounced in rice-wheat than millet-wheat cropping system. Rice crop, though tolerant to soil sodicity, is sensitive to Zn deficiency which may appear 15 to 21 days after transplanting in the form of brown spots on fully matured leaves causing stunted growth and ultimately severe yield reductions (Takkar and Nayyar 1981). Therefore, application of Zn is an important requirement along with gypsum for optimum crop yields in sodic soils/sodic-water irrigated soils (Singh and Bajwa 1987). In sodic soil amended with 10–15 Mg ha^{-1} of gypsum and 10–20 kg $ZnSO_4$ ha^{-1} was enough to meet Zn requirement of crops. The occurrence of Zn deficiency in rice crop could also be prevented by application of FYM and green manure due to reduction in soil pH and ESP and thereby enhanced availability of soil Zn.

Singh (1970) observed that in most soils, exchangeable and active Mn was negatively related with pH and $CaCO_3$. Application of gypsum, green manuring and soil submergence lowered pH and pE and increased Mn^{2+} concentration in the equilibrium solution (Sadana and Bajwa 1985). In gypsum-amended alkali soil, growing rice and wheat for two decades resulted in a decline in DTPA-extractable Mn to 2.7 mg kg^{-1} soil. Due to autoxidation of Mn, it is very difficult to correct Mn deficiency by soil application of $MnSO_4$. Foliar application of Mn is, therefore, effective and economically better than soil application. Repeated sprays (3–4 times) of 1% $MnSO_4$ solution are needed to correct deficiency of Mn in upland crops (Swarup 1998). Due to low permeability in unreclaimed/partially reclaimed sodic soils, Mn deficiency can be expected to be lower due to less leaching losses than normal soils. However, substantial leaching losses of Mn were reported to occur following gypsum application in a sodic environment (Soni et al. 1996).

27.12 Management of Irrigation Water

27.12.1 Conjunctive Use

Combined use of canal and sodic waters is a good option for reducing sodicity hazards of irrigation water on soil health and crop productivity. This is particularly relevant to the areas where canal water supplies are either unassured or inadequate, and farmers often pump sodic groundwater for supplemental irrigation. For efficient use, good-quality waters can be used to grow sensitive crops and sodic waters for tolerant crops. In some situations, poor- and good-quality waters are available either simultaneously or at intervals. The appropriate options include (i) diverse quality waters can be blended in the supply network making tailor-made water available for each crop and all soil conditions (Minhas and Gupta 1992), (ii) alternating the use of good- and poor-quality water (Choudhary et al. 2006; Choudhary 2017) and (iii) switching these water sources according to critical stage of crop growth during the growing season. A seasonal cyclic use, called ‘dual rotation’ strategy, for adoption was advocated by Rhoades et al. (1992) where nonsaline non-sodic water is used for salt-sensitive crops or initial stages of tolerant crops to leach out the accumulated salts from irrigation with salty waters grown to previously tolerant crops. Similarly, Sharma et al. (2005) also agreed that this strategy may work better in arid climate with very low rainfall, but it is of natural occurrence in the monsoonal climate.

Blending is a promising practice in areas where freshwater supplies can be made available on demand. Mixing of sodic and canal water is done in such a proportion so that final SAR/RSC is maintained below threshold limit of the crop to be grown. The proportion of blending two different water supplies (canal and sodic water) depends on the sodicity tolerance of crops to be grown.

Alternating irrigations with good-quality and sodic waters maintained the ESP at relatively lower levels and helped in sustaining good yields of rice and wheat (Table 27.5), sunflower and cotton. Choudhary and Ghuman (2008) observed greater decline in seed cotton yield (16.5% year^{-1}) than that in wheat yield (5.9% year^{-1}). Compared with the SW treatment, yield of cotton and wheat was higher (93–98%) when the irrigation cycle started with CW and involved one SW (2CW: SW, CW:SW). The yields of cotton and wheat also remained higher in an irrigation cycle starting with SW followed by 2CW irrigation (SW:2CW). But with cycles (SW:CW, 2SW:CW) involving one CW, the decline in seed cotton yield was relatively greater (18–23%) than in the wheat yield (10%) after 6 years.

Long-term sustainability of 2CW:SW, CW:SW and SW:2CW was confirmed during the next 6 years (7–12 years) when optimum wheat and cotton yields (90–96% RY) were achieved (Choudhary 2017). This trend was also confirmed by sustainable yield index values after 6 and 12 years (Table 27.6). The SYI indicating the minimum guaranteed yield as referenced to the maximum observed yield (Y_{max})

Table 27.5 Effect of conjunctive use of sodic and canal water on crop yields (Mg ha^{-1}) under different cropping systems

Irrigation	Rice-wheat[a]		Cotton-wheat[b]		Cotton-sunflower[c]
Treatments	Rice	Wheat	Cotton	Wheat	Sunflower
Canal water (CW)	6.78	5.43	1.32	5.20	3.28
Sodic water (SW)[@]	4.17	3.08	0.95	4.43	2.55
2CW:SW	6.67	5.22	1.26	5.10	2.99
CW:SW	6.30	5.72	1.21	4.95	2.88
CW:2SW	5.72	4.85	1.15	4.70	2.67
SW:2CW			1.22	4.82	3.01
SW:CW			1.08	4.70	2.80
2SW:CW			1.02	4.75	2.69
LSD ($p = 0.05$)	0.60	0.50	0.18	0.21	

Source: Bajwa and Josan (1989a), Choudhary et al. (2006) and Choudhary and Ghuman (2008)
[a]1981–1985; [b & c] 1996–2002: [@]RSC > 5 me L^{-1}

Table 27.6 Effect of different cyclic modes of irrigation on crop yields (t ha^{-1}) under cotton-wheat rotation under different time periods

Irrigation treatments/cyclic modes	Wheat				Cotton			
	1996–1997 to 2001–2002		2002–2003 to 2007–2008		1997 to 2002		2003 to 2008	
	Mean	SYI[#]	Mean	SYI	Mean	SYI	Mean	SYI
CW[@]	5.20f[*]	0.79	5.21d	0.85	1.32d	0.54	2.02d	0.55
SW	4.43a	0.65	4.07a	0.61	0.95a	0.41	1.31a	0.35
2CW:SW[$]	5.10ef	0.77	5.01d	0.83	1.26 cd	0.53	1.93 cd	0.57
CW:SW	4.95 cd	0.75	4.88 cd	0.81	1.21bcd	0.51	1.85bcd	0.55
CW:2SW	4.70b	0.72	4.61bc	0.73	1.15bcd	0.49	1.64abcd	0.51
SW:2CW	4.82bcd	0.73	4.88 cd	0.81	1.22 cd	0.56	1.82bc	0.55
SW:CW	4.70b	0.71	4.63bc	0.73	1.08abc	0.47	1.59abc	0.45
2SW:CW	4.75bc	0.73	4.31ab	0.66	1.02ab	0.42	1.52ab	0.44

Source: Choudhary (2017)
[@] *CW* canal water, *S* sodic water
[$]Cyclic use of 2CW and one SW irrigation
[*]Means sharing the same letter(s) in a column do not differ significantly at $p < 0.05$
[#] *SYI* sustainable yield index

with canal water (CW). It ranged from 0.55 to 0.57 for cotton and 0.81 to 0.83 for wheat in 2CW:SW, CW:SW and SW:2CW treatments after 12 years, respectively. The SYI values were higher by 0.06–0.11 for cotton and 0.10–0.15 for wheat compared with that of CW:2SW, SW:CW and 2SW:CW treatments. Largely, lower SYI values for cotton may have been due to large variability in seed cotton than wheat yields in different years. It indicates that even though pre-sowing irrigation to cotton should be always given with good-quality CW for ensuring better germination, viable seed cotton yield can also be attained even with occasional pre-sowing irrigation with SW followed by 2CW (SW:2CW). This treatment simulates the situations where availability of CW is not assured at the time of sowing. It was due to lower build-up of ESP (ESP < 10 in the 0–0.30 m soil layer) in SW:2CW treatment (similar to that observed in 2CW:SW). However, decrease in seed cotton yield was relatively more (18%) than in wheat (10%) when pre-sowing irrigation was given with SW in a cycle involving only one CW (SW:CW and 2SW: CW) during the first 6 years. Relatively higher build-up of ESP in these two treatments possibly deteriorated physical properties of soil to which cotton is more sensitive at germination stage. Higher reduction in seed cotton (25%) and wheat yields (17%) during 7–12 years suggested that these cyclic treatments were not sustainable on a long-term basis for cotton-wheat system.

Greater proportions of SW used in cyclic option can also lower the quality of the harvest. Reduction in onion and potato grade and weight loss during storage was observed to be higher under SW irrigation and the treatments with more number of SW irrigations in a cycle (Chauhan et al. 2007; Chauhan and Kaledhonkar 2018). The proportion of 'A' grade potatoes and onion bulbs was higher in 1TW:1SW cyclic mode that was at par with good-quality water (TW) irrigation.

27.12.2 Irrigation Interval

A general recommendation under sodic soil conditions is to apply light and frequent irrigations for overcoming the effects of poor hydraulic properties of soils. Conversely, under arid conditions, higher transpiration rates from wetter soils due to frequent saline irrigations may lead to increased soil solution salt concentration (1.5- to 2.0-folds) adjacent to growing roots, thus disapproving the case for a higher irrigation frequency.

Bajwa et al. (1993) in a long-term study showed that crop responses to short irrigation intervals with sodic and saline-sodic waters depended on the season in which crop was grown and its relative salt tolerance. Frequent irrigations during summer season moderated the soil temperature and, thus, increased crop yield over the long irrigation intervals.

27.12.3 Irrigation Method

Method of irrigation plays an important role in distribution of water and salts. In India, the surface irrigation methods like check basins, border strips and furrow are the oldest and are most commonly practiced. Nevertheless, these irrigation methods result in excessive irrigation and non-uniformity in water application. Thus, on-farm irrigation efficiency (50–60%) of such irrigation methods is low (Minhas 2012). Irrigation with high energy pressurized methods such as sprinkler and drip is more efficient as the amount of water to be applied can be controlled effectively. The drip irrigation has revolutionized the production of some high-value crops. Due to formation of wetting front by the movement of water due to regular and frequent water supply in drip irrigation, salts are pushed away towards the periphery of the

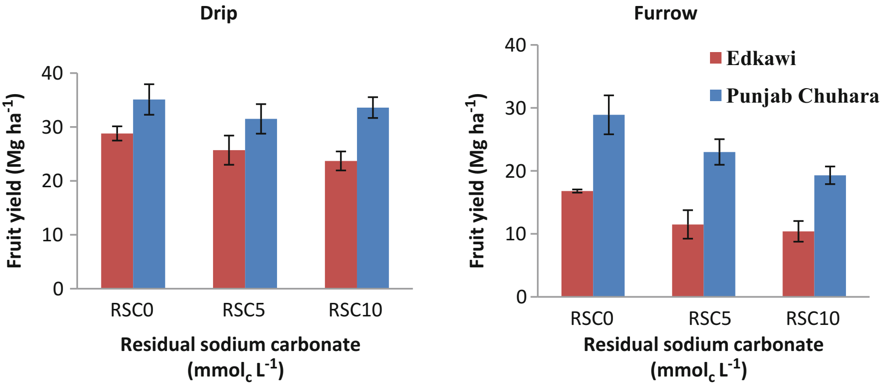


Fig. 27.5 Yields of tomato (Mg ha^{-1}) as influenced by irrigation water with varying RSC under drip and furrow irrigation (after 3 years in 2003–2004). (Source: Choudhary et al. 2010)

front. Thus, drip irrigation has the potential to enhance the threshold limits of crop salt and Na tolerance by modifying the pattern of salt distribution. This resulted in superiority in water use efficiency and yield, as well as size and quality of vegetables. Choudhary et al. (2010) observed that irrigation of tomato with sodic water high in bicarbonates causes more severe effects on soil physical and chemical properties in furrow than in drip irrigation. On the other hand, irrigation with medium and high RSC water under drip irrigation can lead to higher tomato yields than under furrow irrigation due to better soil moisture conditions and lesser deterioration in soil properties (Fig. 27.5).

In general, greater soil and water sodicity causes reduced fruit quality. Nonetheless, superior fruit quality can be obtained in drip-irrigated tomatoes at higher RSC. The other advantage with drip system using saline-sodic water application is that it avoids leaf injury to plants as with sprinklers and maintains optimum conditions for water uptake by their roots.

27.12.4 Leaching Requirement

The first requisite for crop production in saline soils is to lower salinity to acceptable limits, which is accomplished through process of leaching. The extent of leaching required during reclamation depends upon initial salinity, salt tolerance of plants to be grown and depth of water table. Another recommendation is use of excessive water to meet the leaching requirement (LR) and maintain a necessary salt and water balance in the soil with adequate drainage. The concept of LR for achieving salt balance holds good for situations with very low rainfall. But it is of natural occurrence in monsoonal-type climate where rains are concentrated in 2–3 months. In general, LR increases with salinity of water supply and sensitivity of the crop for salinity. However, higher salinity (30–50%) build-up even in light-textured soil was observed when 50% extra saline water was applied to meet the leaching requirement.

Even under alkali water irrigation, salinity control could not be achieved by applying 50% extra water under rice-wheat and maize-wheat systems (Minhas and Bajwa 2001; Choudhary et al. 2011b). Rather such a practice resulted in 40–50% higher build-up of ESP and salts which lowered crop yields. A general strategy to use more efficiently the monsoon rainwater for LR to maintain low salt build-up in the root zone soil appears to be more suitable.

27.13 Conclusions and Future Research Needs

Reports indicate that use of sodic waters for irrigation for crop production will increase in the future. But indiscriminate use of these poor-quality waters can directly and indirectly affect the soil quality parameters and reduce crop yield. Therefore, adopting site-specific management options are crucial for controlling build-up of salts in soils ensuring their safe use for sustainability of crop production. Selection of suitable crops, crop cultivars and cropping patterns that produce higher yields under Na-rich environments are important. Options like conjunctive use of poor-quality water with canal water, appropriate irrigation methods and scheduling and leaching strategies are important to reduce Na and salt build-up in soil and maintain crop yields. The optimum usage of chemical amendments and fertilizers including time and mode of their application and their combined and judicious use along with organic materials will ensure better utilization of these inputs to ameliorate the soil and water sodicity and thereby reduce wasteful losses of water and nutrients. Microbial-mediated calcite dissolution to reduce soil and water sodicity looks promising and should further be explored.

We believe that the time has come to consider these sodic groundwaters as useful resource rather than as environmental burden. Adopting specific systems of management while using these waters should therefore give us an opportunity shift from subsistence farming to progressive farming. A holistic approach should also consider long-term sustainability of employing management and amelioration efforts while using sodic waters site not only in terms of crop productivity but also environmental implications and socio-economic impacts these initiatives will be expected to have on the livelihoods of the affected farming community

27.14 Policy Issues

The following policy issues should be framed and adopted by various stakeholders in order to sustain crop production while using sodic waters for irrigation.

- Policy on water quality monitoring network.
- Modifications in surface water delivery schedules to facilitate and promoting conjunctive use of sodic water with canal water.
- Subsidy on amendments.
- Guidelines for promoting sodic water use through micro irrigation techniques.
- Capacity building and participatory planning.

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Part V

Impact Assessment, Policies and Socio-economic Issues

28

Approaches and Methodologies to Socio-economic Synergies with Ecological Sciences

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Abstract

The evaluation of biophysical and socio-economic effects in ecological sciences considers both qualitative judgement and quantitative techniques like modelling. The stakeholder analysis is a powerful and potential tool in natural resource policy and programme development. The important approaches towards natural resource management comprise of inclusive and integrated advancement of various natural resources on the watershed basis, context-specific and need-based advancement of different natural capitals, natural resource management through integrated farming systems, and locally managed food security system based on native crops and commodities duly supported by the procurement process, price support and public distribution system (PDS). Better socio-economic synergies to ecological problems can be achieved by enhancing communities' capacity to cope with climate extremes. Continuous institutional support should be provided to the farmers and local communities in adaptation to the changing situations and taking initiatives to enhance adaptive capacity and resilience to climate change. Peoples' participation is crucial in attaining synergy between economic developmentand maintaining ecological resource base and level of peoples' participation influenced by the role of groups, organizations and stakeholders in the process. Involvement of local people right from the project design to implementation, monitoring and evaluation level is essential in participatory natural resource management. Participatory watershed management creates a self-managed system and is essential for the sustainability of the economy. Stakeholders should be given opportunities for conferring their desires, appraising the opportunities and prioritization. Different countries have experienced different levels of success in the use of community-based approaches in

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environmental management on awareness, equity, empowerment and sustainable resource utilization, conflict resolution and biodiversity protection.

Keywords

Socio-economic synergies · Ecological sciences · Ecosystem services · Stakeholder analysis · Watershed approach · Biodiversity protection · Empowerment · Public distribution system · Peoples' participation

28.1 Introduction

Ecological and socio-economic systems are highly interrelated. The sustenance of livelihood systems has been largely dependent on ecological system of any area. Ecosystem services are important and critical to livelihood improvement. While ecological degradation leads to poverty, it is aggravated too due to poverty. It sets in poverty-environment trap (Finco 2009). Ecological conservation and poverty alleviation are issues of serious concern while pursuing the much-avowed task of attaining sustainable development goals. Ensuring an equilibrium between socio-economic growth and environmental safety has assumed great significance in planning. Creating a synergy of ecological and socio-economic perspective is the need of the hour for sustainable development. However, for sustainable development, the ecosystem and the social system cannot be studied separately; rather they should be studied jointly and their link should be explored properly. Environmental governance is more effective when social, economic and ecological dimensions are considered and combined and proper attention is given to their interaction. It has become imperative to integrate human dimension in environmental risk assessment and management. As it is observed that different disciplines follow distinct methodologies and deal with different set of information for the risk quantification, therefore, socio-economic and ecological sciences should jointly pursue a comprehensive study to shape different legal frameworks like plant protection regulation, biocide regulation, etc. (Péry et al. 2013).

The Millennium Ecosystem Assessment (MA) gave significant importance to a relatively new concept 'ecosystem services' in 2005. The ecosystem services encourage to study the relations between ecosystems and human well-being in unique ways and offer the more cohesive answers to the difficulty of understanding the nature, the scale of ecosystem degradation, and the strategy that might be required for the upcoming ecological alteration (Haines-Young and Potschin 2009). The socio-cultural and economic value of different ecosystem services delivered by agro-ecosystems was assessed by different scholars by meticulously collecting information through focus group discussion and choice preference modelling. Several attempts have been made to assess the perception of farmers on the important ecosystem services and to assess the economic worth of these services in the form of willingness to pay (Bernues et al. 2014). Different human activities like farming practices have a significant effect on the biodiversity value (McCracken and Huband 2005), the preservation of the cultural landscape and prospects for recreation (Sayadi et al. 2009) and the protection against natural hazards (Ruiz-Mirazo et al. 2011). A specific socio-ecological framework is required by agro-ecosystem service-based management which illustrates representation of the ecosystem and the social system and the dynamic relation between them (Lescourret et al. 2015).

The management of ecosystem services has become the prime focus of present time research and policy and requires a specific socio-ecological framework. In order to draw more integrated answers to the problem of ecosystem degradation and future environmental change, the links between ecosystems and human well-being must be evaluated in a more holistic way. Techniques like quantitative modelling and qualitative expert judgement are utilized to assess the biophysical and socio-economic effects in ecological sciences. Several critical issues exist on this topic which can only be clarified through more powerful tool that has significant potential in natural resource policy and programme design.

28.2 Socio-economic Approaches to Natural Resource Management

The working group on natural resource management (NRM) of 11th Planning Commission of the Govt. of India has suggested four approaches for NRM, i.e. context-specific and need-based advancement of individual natural capital, exterior to the watershed; integrated farming systems-based natural resource management in rainfed areas, within and outside the watershed; inclusive improvement of various natural resources on the basis of watershed; and local food security system suitably supported by price support, procurement and inclusion in the public distribution system (PDS). The report also highlighted the significance of supremacy and the task of National Rainfed Area Authority, National Rural Employment Guarantee Scheme, other significant national bodies and programmes shaped in current years, assimilation and synchronization of processes and strategies, databases and information systems, resource mapping and participatory approaches in the background of NRM.

Kellert et al. (2010) carried out five case studies in Nepal, the US states of Alaska and Washington, and Kenya on community natural resource management (CNRM) and collected empirical evidence regarding the execution of CNRM. The cases were evaluated and compared using six social and environmental indicators including equity, conflict resolution, empowerment, biodiversity protection, knowledge and awareness and sustainable resource utilization. Despite earnest attempts and some success, serious deficiencies were widely observed in the study. It was observed that CNRM in North America was more successful. The differences were observed by institutional, environmental and organizational factors. In contrast, CNRM in Nepal and Kenya rarely resulted in more equitable distribution of power and economic benefits. It has resulted in increased consideration of traditional or modern environmental knowledge, reduced conflict, protection of biological diversity and sustainable resource use. Limnirankul et al. (2015) assessed the vulnerability situation of the Karen community of Northern Thailand. The enhancement of community-based natural resource management with respect to food security and agricultural systems was carried out. It was found that demographic transition and movement, declining availability of suitable agricultural land, hastened environmental depletion and rising use of restricted forest resources were responsible for endangering the conventional rice-based farming livelihoods of the farmers of Mae Khanad watershed. It was also observed that few households experienced rice deficits for 3–7 months. In spite of income disparity between the communities, there were certain factors which were responsible for paving way for capable management of natural resources. These were the mutual relationships between the lowland and upland-highland villages, managing the communal irrigation systems effectively and reciprocal understanding between the local conservation officials and the Karen communities which also helped in lessening the land use disputes. Ali et al. (2014) stressed the importance of participatory approach for the management of forest-related natural resource management. The key pre-requisite for successful implementation of participatory approach is the effective construction and mobilization of beneficiaries group like Village Development Committees (VDCs). Village Development Committees play an influential role in mobilizing the native communities.

Bellamy et al. (2001) formulated the systems approach to evaluate the initiatives for managing natural resources. A set of principles were developed for the evaluation in NRM. Bellamy et al. (2001) suggested that appraisal should address from a systems point of view; objective should be connected with outcome; basic hypotheses and assumptions that support core programme or policy objectives should be considered; in practice, initiatives should be based on the natural resource, policy/institutional, socio-cultural, financial and logical contexts of implementation; progress and impacts should be monitored and evaluated through suitable and practical criteria; the evaluation process should involve appropriate combination of methodology that includes both qualitative and quantitative methods; and perspectives of various aspects like economic, ecological, social, policy and scientific should be integrated. ICRISAT and its allies (2006) had developed a variety of tools, approaches and methods for NRM; these include simulation modelling, adaptation strategies to climate change, climate forecasting, risk adjustment, geographic information system-based mapping and characterization of soil and water resources, approaches to food security analyses, market studies, socio-economic analysis of farmers' investment decisions, gender analysis for technology choice, extension approaches to support technology adoption, etc.

Grimble and Wellard (1997) advocated stakeholder analysis (SA) as a powerful tool for natural resource policy and programme design. Stakeholder analysis helps to understand a system, trace the changes in the system, identify the key stakeholders in the system and evaluate their interests. Particular features of natural resource management (NRM) which make it suitable for the application of SA are various uses and users of the resource, undefined or open access property rights, imperfect markets, presence of externalities, etc. It includes a classification system that distinguishes among trade-offs and conflicts. Issue of acquisition of practical knowledge, understanding key stakeholders, the factors of resource allocation, framework for incorporating institutional and stakeholder concerns, opportunities and choice in developing the interventions, conflict resolutions, etc. are the main researchable issues for natural resource managers. Vovere and Buģina (2011) classified methods for economic assessment of natural resources in two basic groups, viz. indirect method (employing marked methods such as substitution method, method of productivity or income changes, hedonic method and travel costs method) and direct method (constructed (hypothetic) marked method). The evaluation and management plans of natural capitals should engage a joint system of positive economic approach and normative economic approach. Stucki and Smith (2011) highlighted the catalysing role of National Adaptation Programme of Action for natural resource management in the developing countries. The National Adaptation Programme of Action (NAPA) is an initiative agreed under the UN Framework Convention on Climate Change. But the amount invested to implement the NAPA projects aiming at ecosystem restoration using integrated approaches is not adequate. Sterner and Coria (2013) emphasized on the use of economic policy instruments for natural resource management like permit trading, voluntary carbon markets, Clean Development Mechanism, corporate social responsibility, biofuels, payments for ecosystem services, etc.

28.3 Community-based Approach for Enhancing Resilience to Climate Change

The reality of climate change is now vastly evident in the form of changing weather and rainfall patterns, more frequent extreme weather events and rise in sea levels and temperature. The impacts may be further worsened by increasing water scarcity, frequent floods, droughts and declining soil carbon content (Singh and Pathak 2014). Increasing trend in the concentration of atmospheric greenhouse gases (GHGs) from the post-industrial era and consequent global warming increased global atmospheric temperature by 0.74 °C between 1906 and 2005, and a further increase of 1.1–6.4 °C is expected by the end of the twenty-first century (IPCC 2007). Due to anthropogenic actions, the GHG emissions are growing at an accelerating pace which drives climate change. Over the last five decades, the emissions of GHGs from agriculture and allied sectors have nearly doubled and may increase by additional 30% by 2050 (FAO 2014). Agriculture and deforestation are now responsible for about a quarter of global GHG emissions. All these factors pose a real threat to agriculture *vis-à-vis* global food security and are now affecting every country on every continent. People who are associated with the production, consumption and marketing of agricultural produce, fish, livestock, forests and other natural resources are experiencing crises and disasters. The damage for disasters is increasing as majority of the sectors are not enough responsive and do not have a well-defined coping mechanism. As a result, the poor people are becoming the most vulnerable though they contribute least to climate change. It is predicted that climate change will affect the livelihood, water and food availability, and agricultural incomes in the near future. Throughout the twenty-first century, it is expected that the impacts will increase poverty, hamper food security, and affect economic growth.

Advances in research on bio-physical and socio-economic aspects of climate change have established that changes in climate affect both the natural and human systems across the continents and oceans (Adger 2003; Nelson et al. 2010). Better resilience to climate change and variability can be achieved by enhancing communities' capacity to cope with climate extremes, such as cyclones, floods, droughts, etc. In order to fight against the changing climate and improve adaptive capacity and resilience, steps must be taken by facilitating farmers and local communities to organize themselves for the changing situations (Baas and Ramasamy 2008). The community-based extension is an emerging approach to raise awareness on climate change, mobilize the community and foster adaptive capacity , and develop participatory methodologies. Community-based extension recognizes existing environmental knowledge base, perceptions of the community members and adaptation strategies against climatic risks embedded in societies and cultures. It empowers communities to play a central role in the planning and decision-making processes and takes action based on their own decision-making processes. Within the framework of coherent national policies, decentralization of programmes has emerged as an effective and efficient approach to encourage local adaptation. In order to develop adaptive capacity and build resilience of the rural people, the community-based extension is considered as a cost-effective approach (CARE Climate Change 2018). It is an effective approach to mainstream adaptation process in local to national development policy, to reduce disaster risk, to have effective environmental monitoring and community empowerment, and finally to achieve sustainable growth. The development of location-specific adaptation options must be given special attention as it can not only take the factors like bio-physical, socio-economic and socio-cultural factors into consideration but also manage future projected risks.

28.4 Community-based Forest Management

The management of state-owned forests (some of which share customary tenure and rights under traditional laws and practice) and self-owned forests and agroforests by communities themselves is termed as community-based forest management (Sunderlin et al. 2008). The effective and sustainable management and conservation of forest resources can be achieved by active and agreeable partnership among the local communities and state (Saxena 1997).

The government usually manages the forests with the primary goal of producing timber. The forest-based communities' rights have often been marginalized in the process. The role of community in the conservation of forests was not recognized by the government which often results in the failure of forest conservation programmes. Now it is well established that forests can be conserved through people's involvement at the same time meeting subsistence needs of the community (World Bank

1999). The experiences of ‘Arabari’ experiments in West Bengal and ‘Sukhomajri’ in Haryana also reinforce the synergistic relationship between government and local communities in community-based forest management (Sexena et al. 1997).

The socio-economic lives of forest-dependent communities (FDCs) were successfully transformed from being forest-centred to one based on the money economy by community-based forest management in India. It was found that the community-based forest management has enabled regeneration of degraded forests and had resulted in the elite capture of forest resources, but the quality regeneration was mixed. It is observed from government records that due to the shortage of donor funds for the community-based forest management programs, FDCs are losing interest, and many community-based forest management committees are now non-operational in many states. Community-based forest management-related work compels forest officials to spend more resources disproportionately on a small swathe of forest land which may have implications for biodiversity conservation in the long run (Husain and Bhattacharya 2004). The study by Sundar (2017) argued that privatization of woodlands can be a potential alternative to address these concerns and will allow the shift of traditional linear economy towards a circular economy and get the maximum value in the long term.

28.4.1 Weakness in the Study on Community-based Forest Management in India

Murali et al. (2002) recommended various ways to advance the community-based forest management initiatives after reviewing the weakness in community-based forest management in India. The findings of the review of the evaluation studies of community-based forest management in India are presented here.

- *The extent and intensity of evaluation research*: It was reported that majority of the studies were conducted only in one state and maximum up to four states; therefore, the national-level studies extending majority of the states were lacking.
- *Perspective of evaluation*: Community-based forest management is a multi-stakeholder programme, but it was observed that in most of the studies, equal importance to all the stakeholders was not given. The focus was primarily on the donor agencies such as forest departments, and the standpoint of the major stakeholders such as the village community was poorly addressed. The objectives were set out from the perspectives of donor agencies.
- *Agencies involved in the study*: The exclusion of local communities or FPCs from the evaluation was the main trend, as most of the investigations were carried out by consultants and NGOs.
- *Time frame of studies*: It was observed that most of the studies involved collection of data for research in a single point of time within a short period extending from few weeks to a few months. Periodic review, collection of information at several points of time, time series analysis, and proper follow-up studies are lacking.

- *Concern dealt in evaluation*: Issues like ecological and social issues were often not included, and also biodiversity concerns such as augmentation, management and use did not receive sufficient attention in evaluation studies. Organizational and institutional issues like performance of FPC, organization, membership, gender equity and enticement required for sustainable execution received major attention.
- *Details of analytical and statistical techniques*:

  The scientific validity of the research studies may be questioned as there was ambiguity while reporting, and also details on sampling design, sampling unit, sample size and sampling techniques were not provided in a large number of studies.
- *Sampling and data collection method*: Due to the lack of time and resources, majority of studies adopted small and purposive sampling for data collection. For data collection majorly PRA/RRA method was used. Few studies adopted ecological approaches. Cross-checking of results through the use of multiple methods is extremely missing.
- *Variables and indicators of impacts or performance*: Indicators for the study were not selected with proper methodology, and also there was no appropriate methodology for screening and prioritizing the variables and indicators. Comprehensive conceptual framework was not developed to identify the potential indicators and understand the logical link among the indicators.
- *Reconsidering and accessing the M&E reports*:

  Often the methodology employed in the evaluation process was not properly reported. The reports were not accessible to the outsiders other than the donor and implementing agencies.
- *Effect of M&E studies on policy-making and practices*: The final objective of the M&E studies, utilization pattern of evaluation findings and their contribution in policies and practices were not transparent.

28.5 Participatory Watershed Management Approach

Participatory watershed management creates a self-supporting system and is essential for sustainability of economy. It gives an opportunity to the actual users to jointly negotiate their interests, set priorities, explore opportunities, implement the programme, monitor the progress and evaluate the outcomes (Wilson 2002). Watershed management programmes have been perceived as an approach for caring the people's livelihood in the fragile ecosystem where water scarcity, soil erosion, forest degradation, etc. are limiting the economic well-being. Watershed management in India is increasingly understood as an integrated approach for rural development (Joy 2004) which aims to ensure the availability of fuelwood, fodder and drinking water, raising the income and employment of landless laboures and farmers through increase in crop production and productivity. It has become the key intervention in case of natural resource management (Turton et al. 1998). It is a step towards the conservation, regeneration and judicious utilization of indigenously available resources to bring an optimal equilibrium in the ecospace, natural resources, human beings and grazing animals (Khanna 2005). There are certain changes in watershed management such as the structural and nonstructural, activities which result in the ecological parameters, for example, in situ soil moisture condition, land use, vegetative cover, groundwater level, etc., and their economic impact (Singh 2017). Thus, it is a multisectoral and multidisciplinary approach involving continuous interaction and exchange between and among different stakeholders (Butterworth et al. 2010). The goal of watershed management is to integrate social resource management with natural resource management and the judicious use of the natural resource with an active contribution of institutions and organizations, in harmony with the ecosystem (Jain 2004). The major part behind the success of watershed management programme is the philosophy behind it (Reddy 2000). The task is to nurture and encourage sustainable and productive land use systems as well as to protect critical resources and ecosystems by balancing land, water and other resource uses, which provides a basis for negotiation, conflict resolution among stakeholders and participatory decision-making, and to facilitate better social and economic environment (GoI 2002a, b).

The key components for watershed management are collective action, sustainability, equity and people’s participation. Sustainability in terms of socio-cultural indicators (such as women empowerment, farmer groups/self-help group formation, improvement in quality of life, change in land ownership and harmonious social life); economic indicators (such as income level, food security, standard of living, off-farm income to families, rural economy, credit and market supports); and environmental/ecological indicators (such as productive potential of resource base, management of common property resources and biodiversity) could be considered. While equity needs can be fulfilled by equitable access to livelihood resources for the watershed community. Participation in decision-making that results in empowerment where other stakeholders can play only a supportive role (Khanna 2005) can be facilitated. The role of community organizations, groups and other stakeholders is crucial for achieving the desired level of people’s participation. Involvement of local people right from the project design to implementation, management and monitoring level is an essential ingredient for watershed management. Participatory watershed management (PWM) method is perceived as an epitome and fits to the system for achieving food security and sustainability (Kerr 2002).

28.5.1 Impact of Participatory Watershed Management: Indian Experiences

Watershed management approach has been taken as rural development strategy anticipating that it would enhance agricultural income, productivity and natural resource conservation through the process of participatory management (Samra 1999; Sharma and Scott 2005). Several studies have revealed that it had a positive impact on crop productivity, soil moisture content, resource conservation (Shah

2001), increase in cropping intensity (Renfro 2005), control on soil erosion (Kerr et al. 2002), increase in water storage capacity and increase in local water resource stock, reduced runoff and increase in the groundwater recharge (Butterworth et al. 2001). Sen (2008) expressed that the impact analysis through participatory action was carried out more efficiently by the NGO-implemented projects. The impact of participatory watershed management on different aspects of life (agricultural yield, farm revenue, soil and water conservation, rural employment and crop diversification) was assessed by different researchers taking examples from different geographical conditions of the country.

Singh et al. (2002) made an attempt to document the successful impacts of integrated watershed management measures from the perspective of increase in crop yield, water and soil moisture conservation, social forestry, peoples' participation and involvement of women and local-level institutions. Authors concluded that the reason for the success in watershed programme was mainly due to appropriate integration of technical measures (systematic watershed development work, prioritization of water conservation measures and the efficient use of harvested water for supplementary irrigation) and managerial measures (peoples' participation and involvement of various water user groups in the entire process from inception to implementation).

There are many reviews on the performance of watershed management programmes in India (Rao 2000; Joshi et al. 2004; Kerr et al. 2000; Palanisami et al. 2002; Joy et al. 2004) which highlighted several shortcomings of participatory watershed management programmes that include:

- Productivity gains are usually short-term and limited
- Marginal and landless farmers are not much benefitted which increases the disparities at the village level
- Limited attention in common lands
- More attention to irrigation purpose and inadequate attention to domestic, livestock and ecosystem water.
- Downstream effects of exhaustive upstream water conservation are not taken care of
- High costs are incurred to achieve small gains
- Lack of awareness and institutional support and limited participation of people
- Lack of infrastructure and institution building to achieve enduring sustainability of the process

Sharma and Scott (2005) raised the issue of scale and indicated that by the collaborative efforts of NGOs, research institutes and other government departments, successful watershed programmes are being implemented in India in few villages but on a small scale. Institutional mechanism is not adequate to replicate the successful endeavour in large scale. States like Madhya Pradesh and Karnataka in India have been more successful because they were implemented in mission mode.

28.6 Socio-economic Approaches for Flood and Coastal Management

There are certain combination of advanced quantitative modelling techniques and qualitative expert judgement to evaluate hydraulic, hydrological, ecological, social and economic effects of flood control policies. The cost-benefit analysis (CBA) and multi-criteria analysis (MCA) provide a scope to integrate results of ecological, economic and social impact assessment (Brouwer and Van 2004). The need of the hour is to understand the interrelations of social dynamics of flood, risk perception, preparedness, vulnerability, etc. and integrate them in flood damage research and flood management strategy (Messner and Meyer 2006). The extent of damage in flood depends not only on the intensity of the event but also on the coping capacity of the community, preparedness, sensitivity of the system, etc. For the designing of integrated coastal management, it is necessary to understand the socio-economic aspects of coastal folks, ecological issues of coastal ecosystem and exposure of coastal system to the environmental externalities.

28.7 Harnessing Indigenous Technical Knowledge and Local Knowledge Base

The interdisciplinary research approach is more required to understand and address the intricate nature of sustainable natural resource management. Participatory research is being extensively implemented as an alternative solution to multifaceted problems of natural resource management. It has been observed that participation and knowledge of indigenous folks have great importance in natural resource management at community level. It is also a true fact that injudicious and supply-driven adoption of modern technology in indigenous community has increased the rate of depletion of their natural and social resources (Murdoch and Clark 1994; Norgaard 1992; FAO 1990; Ulluwishewa 1993). Recognizing the knowledge ownership, valuable skills, technologies and strategies for solving problems among local communities is crucial in preservation of indigenous knowledge system. It is perceived that scientific and indigenous knowledge complement each other (Ogunbameru and Muller 1996).

Wisdom held by local people who are closely connected with nature for their livelihood are termed as traditional ecological knowledge, or, in general, local ecological knowledge (LEK). LEK facilitates understanding of the complexities of environmental change for policymakers, managers and researchers and complements conventional ecological research (Stave et al. 2007; Brook 2008). When the outcome of the conventional research contradicts the local values and belief, usually it is questioned by the local communities (Tesh 2018). The documentation and validation of local knowledge help in bridging the gap between traditional knowledge and scientific knowledge and paved way for the exchange of ideas between local people and scientists (Turner et al. 2000; Kuhn 1962). The number of the peer-reviewed publications is rising with the popularization of the LEK (Duerden and Kuhn 1998; McGregor 2000).

Some challenges identified in the integration of scientific and local knowledge are identified by Raymond et al. (2010):

- Ontological challenges: Knowledge has been categorized in various ways.
- Epistemological challenges: Integration of knowledge is influenced in different ways because of the logical and epistemological views held by the researcher.
- Application challenges: Problems involved in applying integrated knowledge for the management of environment.

Copa and Tan (2017) advocated that to bridge indigenous knowledge system and scientific knowledge system, it is necessary to recognize the role of each other, promote continuous dialogue among cultures and emphasize socio-cultural elements in integrated resource management approach.

28.7.1 Social Learning Approach to Ecological Conservation

Social learning is a process where change in understanding takes place in an individual as well as in broader social units due to interactions among members in a social system.

Collective action and reflection (Keen et al. 2005) facilitate social learning and improve the management of the interrelationships between social and ecological systems. People collectively engage themselves to understand the problem, define the problem, discuss to come with effective solution for the problem and finally act accordingly to manage the concerned problem. In present scenario, social learning is getting extensive attention in the areas of environmental management (Armitage et al. 2008) and issue of sustainability (Luks and Siebenhuner 2007).

This collective learning, sharing of knowledge and co-creation of the knowledge among the stakeholder go beyond the individual to the social system through social networking. Thus, it creates a huge awareness among the people on ecological issues prevailing in that area. Social learning is also being progressively used for ecological issues regarding local and nutritional food policies where individuals in participatory mode influence the local people for use of traditional foods for nutritional enhancement (McCullum 2004). Social learning is more successful in influencing people because it develops knowledge through critical and contextual analysis of the local system by involving local stakeholders which gives more understanding of the situation to the people. The farmers of Haryana district gained principle knowledge on zero tillage system for management of saline ecosystem through social learning process where they had used information *kiosk* as a social learning platform (Priyadarshni and Padaria 2018). The group discussions on suitability of the technology in their situation and sharing of experiences led to stronger trust and relationship among the farmers besides application of technology in their field, which resulted in higher crop yield. Social learning made an intensive impact on reducing environmental problem like stubble burning. In Haryana and Punjab area, crop residue burning has been a common practice among farmers which has a devastating environmental impact. So, active farmers spread awareness among other farmers about the negative impact of stubble burning and also the alternatives to manage the crop residue through social networking. This had significantly reduced stubble burning in the Mewat district of Haryana (Priyadarshni 2017).

To examine the intricacies of relations and ties between individuals and their personal network members, social learning approach can be used (Wellman 1997). In support of this, Park (2003) monitored and modelled communication habits and patterns among the members of groups. Intensive social interactions of organizational actors facilitate the transfer of knowledge (Lane and Michael 1998; Yli-Renko et al. 2001; Zahra et al. 2000).

Social learning enables more flexible and adaptive sustainable environment management as it uses mental models for analysing environmental problem and identifying strategies and measures (Pahl-Wostl and Hare 2004). To speed up the capacity development and minimize exposure to uncertainty, many firms can act as facilitator by developing effective social networks among innovators and other stakeholders (Grant and Baden-Fuller 1995).

Wenger (1998) in his concept of 'communities of practice' has reflected learning as participatory process where individuals interact and act together to embed themselves into their culture and history. This cultural and historical implantation among people through social learning is even successful in managing river basin issue across Europe (Mostert et al. 2007). Social learning has immense potential to change social structure through interaction and exchange of knowledge between individuals, which can influence the identity of individual in the social surrounding and can shape their living standard.

28.8 Way Forward

The synergy of social and ecological sciences needs emphasis through due considerations to the imperatives of both sciences in order to find solutions to emerging issues related to developmental pathways and environmental considerations. There is a need for development of common guidelines to record baseline as well as longitudinal monitoring data, which could be useful in analysing the impacts of current and future activities. It will also facilitate and plan corrective measures based upon mid-term evaluation (Singh, 2017). Establishment of an institutional mechanism by involving reputed national and international organizations will enhance the quality of monitoring and impact assessment in watershed. The evaluation also needs to be properly designed and carried out by the third party which could include professional teams independent of implementing agencies. Satellite imageries of land use, land cover, cropping and greenness index for both sets covering the pre-intervention phase and post-implementation phase could be useful in assessing the differences in respect of the extent and quality of forest tree cover, intensity of land use and cropping pattern. Further, this should be supplemented by sample surveys of the farms and fields to ascertain the changes. Besides mapping and characterizing the natural resources and landscapes, engagement of social scientists and use of socio-economic assessment methods should be integral elements of the framework. The resource endowments of communities, livelihood considerations, local knowledge systems, traditional ways of conservation and utilization of resources, local institutions and their norms and values , and issues related to intellectual property rights regimes related to communities are vital for ecological conservation and redressal. Therefore, synergy needs due consideration. The scientists of both streams need to walk an extra mile to reach out to each other and devise mechanism for the welfare of people as well as ecology.

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Management of Salt-affected Soils in India: Gender and Socioeconomic Dimensions for Sustainable Livelihoods

29

K. Thimmappa, R. Raju, R. S. Tripathi, J. C. Dagar, and R. K. Yadav

Abstract

Women face greater gender-related vulnerabilities compared to men due to prevailing structures in the societies. Recognizing the role of gender equality, development organizations have engaged in a process of mainstreaming gender into agricultural development. World Bank-supported land reclamation programs encouraged women participation to achieve the goals of women empowerment in India. Land reclamation programs contributed vast benefits and sustainable livelihoods to millions of small farmers. Reclamation programs included additional dimensions to support women participation in the programs and to earn income to support the family. A majority of women opined that the management of salt-affected soils increased household income due to increased area under cultivation and productivity. They opined that increased household income lead to increased standard of living, purchasing power, and education status which improved their social status in the society. Women participation in the management of salt-affected soils has positively affected socioeconomic dimensions for sustainable livelihoods.

Keywords

Land reclamation · Salt-affected soils · Women participation · Sustainable livelihoods

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29.1 Introduction

Agriculture is the primary source of employment and income for both men and women in the salt-affected regions in India. Soil productivity is an important asset for poor women and men for sustaining agricultural livelihoods and attaining food security. The degradation of soil due to salinity can severely limit people's livelihoods. In India, agricultural production is being constrained by land degradation resulting from soil salinity and sodicity. The demand for foodgrain projections suggest that India require to produce more food to increasing human population (Radhakrishna and Ravi 1990; Kumar 1998; Kumar et al. 2009), which will result in an increase in the use of marginal-quality land and waters for foodgrain production (Yadav 1981; Oster and Jayawardane 1998; Qadir et al. 2001). Majority of smallholder farmers living in the salt-affected regions supplement their low farm income with off-farm economic activities. In severely salt-affected areas, poor farmers migrate to urban areas for work to secure their livelihood.

Social development, poverty, gender, and environment are major themes of the World Bank and government development schemes, especially within the Sustainable Development Network. As per the World Bank (2001) experiences, disregarding gender inequalities negatively impacts people's well-being and countries' development. The objectives of poverty reduction cannot be achieved while ignoring women, who are the major actors. Hence, development organizations have given major thrust to mainstreaming gender into agricultural development. The World Bank and International Fund for Agriculture Development have implemented gender mainstreaming strategies (World Bank 2009). In India, World Bank-supported land reclamation programs have been implemented in Uttar Pradesh. The project was designed in line with the World Bank's poverty reduction strategy aiming for sustainable natural resource management and enhancement of gender participation.

The contribution of women participation is well recognized in Indian agriculture. However, there is not much literature to recognize the contribution of gender participation in the management of saline agriculture in India. Hence, this chapter provides benefits of salt-affected soil management with a focus on gender and socioeconomic dimensions for sustainable livelihoods in the salt-affected regions of India. The present chapter is based on the socioeconomic study conducted in salt-affected regions in India at ICAR-Central Soil Salinity Research Institute, Karnal, from 2001 to 2017.

29.2 Gender Participation in Saline Agricultural Activities

Women play an important role in saline agriculture and participate in various agricultural and allied activities along with men. The types and extent of agricultural activities in which women are engaged vary in different states. For instance, in the states of Orissa, Tamil Nadu, West Bengal, Kerala, and Kashmir, women are engaged in transplanting, weeding, harvesting, and threshing of paddy. In Gujarat, women participate mainly in weeding, harvesting, and threshing of pulses. Women's participation in farming declines as their position goes up in social hierarchy. The extent of women participation in saline agricultural activities varied from 40% to 65% depending on crops, region, religion, classes, and castes. For example, average contribution of women in sugarcane cultivation activities in saline environment in Karnataka was found to be 41.85% (Table 29.1). The contribution of women in rice and wheat crop cultivation in salt-affected region of Uttar Pradesh varied from 50% to 65%. The agricultural activities in which the women play a leading role in saline agriculture include forming ridges and furrows, transplantation, fertilizer application, weeding, threshing, reaping, looking after livestocks, and fodder collection.

29.3 Gender Participation in Salt-affected Soil Management

Salt-affected soils can be managed based on the amount of salts, type of salts, amount of sodium present, and soil alkalinity. ICAR-Central Soil Salinity Research Institute and state agriculture universities have developed location-specific reclamation and management technologies for salt-affected soils in India. They include chemical, biological, and hydrological approaches (Rao et al. 1994; Tyagi and Minhas 1998; Gupta et al. 2000). Gypsum technology is used to reclaim alkali soils in India. Similarly, combination of surface and subsurface drainage technology approach is used to reclaim saline and waterlogged saline soils. Women participation is negligible in saline soil reclamation as machines are being used to install the subsurface drainage systems. The women participation in alkali soil management is given in Table 29.2. Women participate in land leveling, making irrigation channels and field drains (21%), bund making (33%), and amendment application (38%). Overall women contribute one fourths of labor to alkali soil reclamation in India.

29.4 Impact of Salt-affected Soil Management to Farm Households

29.4.1 Farm Productivity and Costs

Farm households in salt-affected area reclaim their lands through government programs. The land reclamation programs benefited the farmers in terms of changed cropping pattern from cultivation of low-value crops to high-value crops in Karnataka (Mandal et al. 2005; Ritzema et al. 2008) and increased cropping intensity (Datta et al. 2004; Ritzema et al. 2008). Our study indicated that cropping intensity was low (123%) during pre-reclamation period in sodic land and increased to 199% after reclamation (Thimmappa et al. 2015a).

Our study observed that land reclamation had a positive impact on productivity of rice and wheat. The productivity of rice increased by 60% in "slight" soil sodicity category after reclamation (Table 29.3). In "moderate" soil sodicity category, rice productivity increased by 261%. In the "severe" soil sodicity category, rice

Table 29.1 Extent of participation of men and women in sugarcane cultivation activities in saline environment

S. No.	Activities	Men	Percent	Women	Percent	Total
1	Land preparation					
	Plowing	5.00	100.00	0.00	0.00	5.00
	Forming ridges and furrows	5.00	33.33	10.00	66.67	15.00
2	Planting					
	Set cutting	5.00	66.67	2.50	33.33	7.50
	Set treatment	2.50	100.00	0.00	0.00	2.50
	Set transport	5.00	100.00	0.00	0.00	5.00
	Set spreading	5.00	100.00	0.00	0.00	5.00
	Set planting and gap filling	5.00	28.57	12.50	71.43	17.50
3	Application of fertilizers and manures					
	Manure application	5.00	66.67	2.50	33.33	7.50
	Fertilizer application	10.00	80.00	2.50	20.00	12.50
	Foliar spray of micronutrients	2.50	100.00	0.00	0.00	2.50
4	Weed management					
	Hand weeding	0.00	0.00	35.00	100.00	35.00
	Weedicide spray	5.00	100.00	0.00	0.00	5.00
5	Irrigation management					
	Guiding irrigation water	12.50	83.33	2.50	16.67	15.00
	Cleaning channels	12.50	83.33	2.50	16.67	15.00
6	Cultural operations					
	Earthing up	5.00	100.00	0.00	0.00	5.00
	Detrashing and mulching	5.00	66.67	2.50	33.33	7.50
	Tying, wrapping, and propping	5.00	50.00	5.00	50.00	10.00
7	Plant protection					
	Supply of water	0.00	0.00	5.00	100.00	5.00
	Mixing and spraying of chemicals	5.00	100.00	0.00	0.00	5.00
	Rogueing of affected clumps	2.50	50.00	2.50	50.00	5.00
8	Harvesting					
	Cane cutting	12.50	71.43	5.00	28.57	17.50
	De-topping and cleaning of cane	7.50	60.00	5.00	40.00	12.50
	Bundling of cane	5.00	66.67	2.50	33.33	7.50
9	Marketing of cane					
	Loading	5.00	66.67	2.50	33.33	7.50
	Transporting	2.50	100.00	0.00	0.00	2.50
	Unloading	5.00	100.00	0.00	0.00	5.00
10	Ratoon management					
	Collection and disposal of trash	5.00	66.67	2.50	33.33	7.50
	Total	**142.50**	**58.16**	**102.50**	**41.84**	**245.00**

Note: Figures in parentheses indicate percent to row total
Source: Field survey during 2016 and author's estimation

Table 29.2 Gender participation (man-days ha^{-1}) in the salt-affected soil management

S. no.	Particulars	Men	Women	Total
1	Land leveling, making irrigation channels and field drains	11 (79)	3 (21)	14 (100)
2	Bund making	8 (67)	4 (33)	12 (100)
3	Amendment application	13 (62)	8 (38)	21 (100)
4	Irrigation and flushing of salts	9 (100)	0 (0)	9 (100)
	Total	41 (73)	15 (27)	56 (100)

Note: Figures in parentheses indicate percent to row total
Source: Thimmappa et al. (2015b)

Table 29.3 Impact of land reclamation on crop yields

Particulars			Normal	Slight	Moderate	Severe
Rice	Pre-reclamation period	Yield (Mg ha^{-1})	4.87	2.95	1.22	0
		Yield loss (%)	–	39.43	74.95	100
	Post-reclamation period	Yield (Mg ha^{-1})	4.97	4.71	4.40	3.90
		Yield loss (%)	–	5.24	11.48	21.45
	Mean difference between post- and pre-reclamation periods		–	1.76*	3.18*	–
Wheat	Pre-reclamation period	Yield (Mg ha^{-1})	3.65	2.82	0	0
		Yield loss (%)	–	22.74	100	100
	Post-reclamation period	Yield (Mg ha^{-1})	3.74	3.49	3.17	2.75
		Yield loss (%)	–	6.82	15.24	26.60
	Mean difference between post- and pre-reclamation periods		–	0.67*	–	–

Note: In pre-reclamation period, severely sodicity-affected lands were left fallow in both seasons and no crop production in "moderate" classes during *rabi* season
Source: Thimmappa et al. (2015a)
*Significant at $p \leq 0.05$ level

production was 3.90 Mg ha^{-1} which was barren in pre-reclamation period. The study also revealed that wheat productivity increased by 24% in "slight" land category in post-reclamation period. The wheat yield was 3.17 Mg ha^{-1}in "moderate" and 2.75 Mg ha^{-1} in "severe" land sodicity categories in post-reclamation period which were uncultivated in pre-reclamation period. It suggested that a considerable productivity gain was noticed after land reclamation. The yield gain was highest in "moderate" class (3.17 Mg ha^{-1}) followed by "severe" (2.75 Mg ha^{-1}) and "slight" (0.67 Mg ha^{-1}) sodicity classes.

The crop yield losses were substantial ranging from 23% to 100% in pre-reclamation period compared with normal land. The yield losses were noticeably reduced and ranged from 5.24% to 100% in post-reclamation period. Chinnappa and

Table 29.4 Impact of land reclamation on unit cost of production

Particulars			Normal	Slight	Moderate	Severe
Rice	Pre-reclamation period	Costs (₹Mg^{-1})	8560	13,598	30,828	–
		Change (%)	–	59.62	260.15	–
	Post-reclamation period	Costs (₹Mg^{-1})	8951	9431	10,062	11,017
		Change (%)		5.36	12.41	23.08
	Mean difference between post- and pre-reclamation periods		–	4167*	20766*	–
Wheat	Pre-reclamation period	Costs (₹Mg^{-1})	9475	11,232	–	–
		Change (%)		18.55	–	–
	Post-reclamation period	Costs (₹Mg^{-1})	9200	9681	10,457	11,437
		Change (%)		5.23	13.67	24.30
	Mean difference between post- and pre-reclamation periods		–	1551*	–	–

Note: No crop production in “severe” sodicity class land in *Kharif* season. In pre-reclamation period, no crop production in “moderate” and “severe” sodicity class land in *rabi* season
Source: Thimmappa et al. (2015b)
*Significant at $p \leq 0.05$ level

Nagaraj (2007) reported that subsurface drainage technology had positive benefits on crop yield and enhanced crop yield by 166%. A large number of experimental results and on-farm studies revealed that adoption of reclamation technology has given yields on par with the yield of normal soils. (Joshi 1983; Singh and Bajaj 1988; Datta et al. 2004). The higher crop yield in post-reclamation period was due to better soil condition and reduction in the soil salinity level (Raju et al. 2015). Several studies have proved that gypsum use reduced sodium toxicity and improved soil structures which in turn enhanced crop productivity (Chhabra 1996; Rasouli et al. 2013).

Salt accumulation in soils negatively affects production cost. For example, sodicity has enhanced Mg^{-1} cost of rice by 260.15% in “moderate” soil class compared to “normal” soil class in sodic areas of Uttar Pradesh (Table 29.4). The production cost Mg^{-1} of produce increases from lower to higher sodicity classes, due to lower crop productivity at the higher level of soil sodicity. The cost per Mg of rice was reduced by 31% in “slight” soil sodicity category and 67.36% in “moderate” soil sodicity category in the post-reclamation period. The per Mg cost incurred for wheat production was 18.55% higher in “slight” sodicity class in pre-reclamation period and declined to 5.23% in post-reclamation period compared to normal land. This indicates that costs Mg^{-1} of produce declined after reclamation due to higher crop productivity across different soil sodicity categories. A few studies conducted at the Central Soil Salinity Research Institute revealed that about 4–6 years are required for successful reclamation of alkali soils after following recommended reclamation technologies (Chhabra and Abrol 1977; Singh et al. 1998; Tyagi 1998; Swarup 2004).

Table 29.5 Impact of land reclamation on costs and returns (₹ha^{-1})

Sodicity class	Gross return		Total cost		Net returns		Total net returns
	Kharif	*Rabi*	*Kharif*	*Rabi*	*Kharif*	*Rabi*	
Pre-reclamation period							
Normal	77,290	58,320	41,715	34,614	35,575	23,706	59,281
Slight	47,120	45,032	40,351	31,707	6769	13,324	20,094
Moderate	19,470	–	37,597	–	−18,127	–	−18,127
Post-reclamation period							
Normal	79,278	59,740	44,442	34,396	34,836	25,344	60,180
Slight	75,143	55,548	44,366	33,732	30,777	21,815	52,592
Moderate	68,958	50,670	44,214	33,088	24,743	17,582	42,325
Severe	62,275	43,558	42,964	31,342	19,311	12,216	31,527

Note: "Moderate" sodicity category lands were kept fallow only in *rabi* season. "Severe" sodicity category lands were kept fallow in both seasons
Source: Thimmappa et al. (2015a)

29.4.2 Farm Income

Our study revealed that income declined with increased salt content in soil (Table 29.5). The net return increased by 161.73% in "slight" soil sodicity category during post-reclamation period. The improved yield contributed to higher net income across the soil sodicity categories. In the "severe" soil sodicity category, net return was ₹31,527 ha^{-1} which was left fallow in pre-reclamation period. It showed that income could be increased by reclamation of severely degraded barren land. Several studies also have reported that soil reclamation reduced income losses and increased agricultural income (Joshi 1983; Chinnappa and Nagaraj 2007).

29.4.3 Farm Employment

Farmers in the salt-affected area migrate to cities in search of employment. Our study in sodic areas in Uttar Pradesh showed that land reclamation provided additional employment (Table 29.6). The reclamation generated additional farm employment to farmers and his family members. The reclamation of unproductive land generated annual employment 132 man-days ha^{-1} in rice and 70 man-days ha^{-1} in wheat. The contribution of women in rice and wheat crop cultivation in salt-affected region of Uttar Pradesh is varied from 50% to 65%. The reclamation of "severe" category land generated employment of 202 man-days ha^{-1} annually. The total annual employment generation varied from 15 to 202 man-days ha^{-1} depending on the categories of land. The increased cropping intensity, higher productivity, and additional barren land brought under cultivation in the reclamation programs generated additional employment in farm sector (Joshi 1983; Joshi and Singh 1990; Tripathi 2011; Thimmappa et al. 2013).

Table 29.6 Impact of land reclamation on farm labor employment

Particulars			Normal	Slight	Moderate	Severe
Rice	Pre-reclamation period	Employment (man-daysha^{-1})	144	135	117	0
	Post-reclamation period	Employment (man-days ha^{-1})	142	141	140	132
	Additional employment generation (man-days ha^{-1})		–	6	23	132
Wheat	Pre-reclamation period	Employment (man-days ha^{-1})	81	71	0	0
	Post-reclamation period	Employment (man-days ha^{-1})	81	80	77	70
	Additional employment generation (man-days ha^{-1})		–	9	77	70

Source: Thimmappa et al. (2015b)

29.4.4 Food Security and Expenditure Pattern

Food insecurity exists when all people, at all times, do not have physical and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life (FAO 2003). Indian government has introduced a wide range of schemes to achieve food and nutritional security at the household levels. In view of this, one of the programs is land reclamation programs implemented by central and state governments to improve food and livelihood security of poor farmers.

The land reclamation programs have improved food-security status of farm households in Uttar Pradesh. Table 29.7 shows the distribution of households by food-security status. The total rice and wheat requirement per family was estimated from 55th round NSSO survey (2000) for pre-reclamation period and 66th round NSSO survey (2010) for post-reclamation period. The foodgrain requirement was calculated as the difference between the total annual production of rice or wheat and total annual family consumption. It was observed that all categories of farmers produced excess rice than their family requirement. In the production of wheat, smallholders were not able to meet consumption requirement from their own farm prior to reclamation. After reclamation, all categories of farmers produced excess foodgrains due to additional barren land brought under cultivation and significant increase in crop productivity.

Farmers were classified into deficit foodgrain-producing farm households and food self-sufficient farm households. This classification is based on the difference between per household per annum total rice or wheat requirement for consumption and production. The households with annual consumption requirement higher than annual production were classified as food-deficit households and were assumed to have low food-security status. The households with annual production higher than annual consumption requirement were classified as food self-sufficient households.

Table 29.7 Impact of land reclamation on foodgrain production status

Particulars	Marginal farmers	Small farmers	Medium farmers
Family size (no.)	7	7	6
Average farm size (ha)	0.66	1.31	3.09
Pre-reclamation period			
Milled rice			
(a) Production (Mg family^{-1}year^{-1})	0.826	1.330	3.822
(b) Consumption (Mg family^{-1}year^{-1})	0.360	0.360	0.308
(c) Deficit/Excess (Mg family^{-1}year^{-1})	0.467	0.971	3.514
Wheat			
(a) Production (Mg family^{-1}year^{-1})	0.592	1.206	2.953
(b) Consumption (Mg family^{-1}year^{-1})	0.747	0.747	0.640
(c) Deficit/Excess (Mg family^{-1}year^{-1})	−0.155	0.459	2.313
Post-reclamation period			
Milled rice			
(a) Production (Mg family^{-1}year^{-1})	1.509	2.818	7.202
(b) Consumption (Mg family^{-1}year^{-1})	0.356	0.436	0.305
(c) Deficit/Excess (Mg family^{-1}year^{-1})	1.153	2.381	6.896
Wheat			
(a) Production (Mg family^{-1}year^{-1})	1.691	3.516	9.180
(b) Consumption (Mg family^{-1}year^{-1})	0.633	0.714	0.591
(c) Deficit/Excess (Mg family^{-1}year^{-1})	1.058	2.802	8.589

Source: Thimmappa et al. (2013)

Table 29.8 Impact of land reclamation on household's food-security status

Farmers category	Foodgrain	Pre-reclamation period (2000)		Post-reclamation period (2011)	
		Deficit (%)	Excess (%)	Deficit (%)	Excess (%)
Marginal	Milled rice	26.3	73.7	0.0	100.0
	Wheat	68.4	31.6	15.8	84.2
Small	Milled rice	16.7	83.3	0.0	100.0
	Wheat	20.8	79.2	0.0	100.0
Medium	Milled rice	0.0	100.0	0.0	100.0
	Wheat	0.0	100.0	0.0	100.0

Source: Thimmappa et al. (2013)

The distribution of households by food-security status (Table 29.8) showed that 26.3% of marginal farmers and 16.7% of small farmers were not producing required quantities of rice for family consumption during pre-reclamation period. Similarly,

Table 29.9 Impact of land reclamation on household expenditure (%)

Particulars	Increased	Decreased	Constant	No difference
Foodgrain purchase	0	92	8	0
Fruit purchase	17	0	83	0
Vegetable purchase	18	13	68	0
Purchasing of clothes	65	0	25	10
Investment on house construction	78	0	22	0
Education expenditure	73	0	17	10

Source: Thimmappa et al. (2013)

Table 29.10 Poverty status of the selected households after land reclamation

	Pre-project status	Post-project status
Households	Below poverty line (%)	Above poverty line (%)
Landless labors	88	76
Marginal farmers	84	67
Small farmers	72	33
Large farmers	69	26
Overall average	80	55

Source: Tripathi (2009)

68.4% of marginal farmers and 20.8% of small farmers were not producing required quantities of wheat for family consumption. During post-reclamation period, they could sell excess rice in the market. Even after land reclamation, still 15.8% marginal farmers could not produce sufficient wheat required for family consumption due to smaller farm size. Irrespective of farm size, farmers have opined that land reclamation technology brought improvement in their food-security status.

The increased farm income as a result of reclamation changed farm household expenditure pattern. About 92% farmers expressed that foodgrain purchase from the market drastically declined (Table 29.9). Farmers (65%) also opined that purchasing of cloths and other household items increased after reclamation. The expenditures on fruits and vegetables, house construction, and children education were increased during post-reclamation period. Hence, soil reclamation enhanced social well-being of farm families in salt-affected regions.

29.4.5 Poverty Alleviation

The soil reclamation gave unique opportunity to reduce poverty, particularly for marginal and small farmers, who were bound to struggle for their livelihood. Project intervention in Uttar Pradesh resulted in decline of participant households below poverty line from 80% to 55% during a short period of 7 years (Table 29.10). Thus, reclamation programs proved exemplary model for poverty alleviation in the sodicity-affected areas.

29.4.6 Literacy and Quality of Life

The intervention through land reclamation increased cropping intensity, crop yield, and employment opportunities. These all have positive impact on household economy and quality of life of the beneficiaries. The literacy improved remarkably over the years in those areas where sodic land reclamation programs had launched. The male literacy was invariably more than female literacy in the project area irrespective of the category of households. Male literacy improved by 7% and female literacy by 9% after reclamation. It was attributed to the increased awareness among people about education. The number of children enrolled at school registered remarkably high as compared to the number registered before reclamation in those areas where reclamation projects were completed. These facts reflect impact of land reclamation on various important aspects of daily life and decision-making capabilities of the rural women, which have direct positive correlation with the standard of living.

29.4.7 Changing Role of Women in Household Activities

The perception of farmers showed that land reclamation has changed role of the farm women (67%). The perception of farmers on 13 household activities is listed in Table 29.11. The results indicate that there was no more fetching of water from far-off areas as 91% household made this facility in and around the house. In 89% cases animal feeds are chaffed by power-driven chaff cutter, whereas 81% households shifted from manual grinding of flour to power grinders. About 76% households shifted from carrying fodder on the head to tractor or by animal-driven cart. They spent more time for leisure activities (74%). The sodic land reclamation resulted increased mechanical harvesting and threshing (67%), increased practice for ironing of clothes, and increased women migration for education and other works (64%). They have been shifting from animal dung cake to kerosene/LPG/*gobar* gas (58%) for food cooking, and there was no more pasting of floor with mud and dung (55%). They shifted from manual milk churning to churning by machines (41%) and shifted from manual washing to machine washing of clothes (14%). Soil reclamation programs ensured women participation along with poverty reduction due to increased cropped area and production which changed the role of women.

29.4.8 Impact on Decision-making Process

Decision-making was the most important step in the process of land reclamation technology adoption. The percentage respondents citing main decision-maker on the selected farm-family activities are summarized in Table 29.12. It is evident from the results that most of the decisions were taken by the head of the family alone and there was little scope for joint decisions. The family head was responsible for decision-making in the majority of the family activities (11–57%) such as reclamation of alkali soils; quantity of soil amendment to be used; crop varieties to be sown;

Table 29.11 Changing role of women due to management of salt-affected soils

S. no.	Particulars	Extent of change		
		Completely changed	Partially changed	No changed
1	Fetching of water from far-off areas	153 (91)	13 (8)	2 (1)
2	Shift from dung cake to kerosene/LPG/*gobar* gas as cooking fuel	98 (58)	17 (10)	53 (32)
3	Pasting of floor with mud/dung	93 (55)	37 (22)	38 (23)
4	Manual washing to machine washing of clothes	24 (14)	60 (36)	84 (50)
5	Increase in ironing of clothes	107 (64)	54 (32)	7 (4)
6	Leisure time activities	125 (74)	38 (23)	5 (3)
7	Manual grinding of flour	137 (81)	6 (4)	25 (15)
8	Carrying fodder on head	128 (76)	14 (8)	26 (16)
9	Time spent to arrange drinking water to animals	150 (89)	13 (8)	5 (3)
10	Use of power-driven chaff cutter	150 (89)	10 (6)	8 (5)
11	Women migration for education and/or work	107 (64)	37 (22)	24 (14)
12	Manual milk churning	68 (41)	14 (8)	86 (51)
13	Mechanical harvesting and threshing	112 (67)	41 (24)	15 (9)
	Total	1452 (67)	354 (16)	378 (17)

Note: Figures in parentheses indicate percent respondent's perceptual change in role. Word *gobar* stands for cow dung
Source: Tripathi (2009)

nutrient management for crops; purchase of agricultural land; sale of agricultural land; extent of produce to be sold; extent of agricultural land to be leased-in and leased-out; quantity of grains to be stored; grain storage measures to be adopted; purchase of heavy agricultural machinery like tractor, combine harvester, etc.; number of draft animals to be kept; number of milk animals to be kept; type of feeding to be procured for cattle; type of cattle shed to be constructed; and quantity of milk to be sold.

The housewives (spouses) were largely engaged on decisions related to consumption, processing, storage of grains, and quantity of milk to be sold. The sons of the families were involved mainly on decisions related only for the number of drat and milch animals to be kept (13%) and type of fodder to be fed to the animals (9%). The decision-making in crop varieties to be sown, compost pit construction, FYM to be used, purchase of agricultural land, sale of agricultural land, and extent of agricultural land to be leased-in and leased-out were taken jointly by the head of the family, spouses, and sons.

Elder family members were consulted in purchase and sale of agriculture land (24%), extent of agricultural land to be leased-in and leased-out, and purchase of heavy agricultural machinery (18%). The heads of the farm families took decisions with the consultation of their wives ranging from 24% to 44%. However,

Table 29.12 Participation of women in the decision-making in the salt-affected areas

S. no.	Activities	Self	Spouse	Son	Elder family members	Self and spouse	Self and son	Self and others
1	Reclamation of alkali soils	55	0	1	12	25	6	1
2	Quantity of soil amendment use	55	0	1	11	24	7	2
3	Crop variety to be sown	57	0	0	10	24	7	2
4	Nutrient management	57	0	1	7	25	8	2
5	Purchase of agricultural land	1	0	0	24	31	5	29
6	Sale of agricultural land	1	1	0	24	30	6	28
7	Extent of produce to be sold	17	0	2	11	32	6	2
8	Agricultural land to be leased-in/leased-out	17	1	0	18	31	24	9
9	Quantity of grains to be stored for consumption	14	23	3	10	44	6	0
10	Storage measures be adopted	21	2	1	12	37	23	8
11	Purchase of farm machinery	14	0	1	18	32	9	26
12	Number of draft animals to be kept	23	1	13	10	38	15	2
13	Number of milch animals to be kept	20	9	5	11	44	10	1
14	Type of feedings for cattle	29	0	9	11	35	12	4
15	Type of cattle shed to be constructed	15	1	1	15	35	18	15
16	Quantity of milk to be sold	12	25	1	11	44	6	1

Source: Tripathi (2009)

participation of housewife was found to be more effective decisions related to consumption (44%), quantity of milk to be sold (44%), and number of draft animals to be kept (37%). The family heads took joint decision in consultation with their wives mainly in activities like extent of agricultural land to be leased-in and leased-out (24%), type of cattle shed to be constructed (18%), and number of draft animals to be kept (15%).

Table 29.13 Perceptional changes in environment due to management of salt-affected areas

	Perceptual change			
Particulars	Better	Same	Worse	Don't know
Agricultural production	98.8	0.0	0.0	1.2
Pasture lands	8.9	0.0	0.6	90.5
Trees in and around the village	15.5	0.0	0.0	84.5
Drinking water availability	67.3	0.6	0.0	32.1
Waterlogged areas	49.4	0.0	0.0	50.6

Source: Field survey (2015)

The family head along with other members of the family took decisions mainly for purchase of agricultural land, (29%), sale of agricultural land (28%), purchase of heavy agricultural machinery (26%), grain storage measures to be adopted (23%), and type of cattle shed to be constructed (15%). Hence, both men and women make joint decisions in most of the household activities in the salt-affected regions in India.

The results presented in Table 29.13 revealed that reclamation of alkali soils is effective in changing the environment of the area. About 99% of the farmers perceived that the agricultural production increased as a result of land reclamation because the area under alkali soils converted to productive land. There was improvement in availability of drinking water as perceived by 67% farmers followed by improvement in waterlogged area (49%) and trees in and around the villages (15.5%). About 90% farmers reported that there was no improvement in pasture lands mainly due to more land demanded for crop cultivation, which left only the most degraded land for permanent pastures.

29.4.9 Women Empowerment

In poor households, men's earnings are not sufficient for survival of the households. Development programs, therefore, which increase men's income are not successful in alleviating the poverty by diminishing malnutrition or by increasing access to education and health care. Both men's and women's incomes need to be increased to enable households to escape poverty. Therefore, reclamation programs included additional dimensions to support women participation in the programs and to earn income to support the family. About 97% of women opined that the management of salt-affected soils increased the household income due to increased cultivation area and productivity. They opined that increased household income lead to increased standard of living (87%), purchasing power (75%), and education status (77%) which improved their social status of households in the society (Table 29.14).

Salt-affected soil management programs have supported poor households in terms of providing trainings in trades and skills. The project also facilitated beneficiaries to take financial help from banks to start income-generating activities. An alternative credit structure has been established in the form of group saved

Table 29.14 Opinion of women participants about benefits of management of salt-affected soil

S. no.	Particulars	Opinion (%)
1	Increase in the household income	97
2	Improvement in the social status	90
3	Improvement in the purchasing power	75
4	Easy availability of loans with reasonable interest rate	58
5	Freed from the clutches of village moneylenders	67
6	Improvement in the education status	77
7	Improved quality of environment	78
8	Improvement in the living standard	87

Source: Field survey (2015)

money which has helped them to be free from the clutches of village moneylenders. Loans are taken for agricultural purposes, income-generating activities, and domestic need fulfillment (Sahay 1997). Women participation in the management of salt-affected soils has positively affected socioeconomic dimensions of women empowerment.

29.5 Conclusion

Salt-affected soils severely limit crop productivity and adversely affect food security of farm families. Reclamation programs significantly helped to achieve food and livelihood security of poor farmers. The gender participation in management of salt-affected soils enhanced women empowerment. Land reclamation programs contributed enormous socioeconomic benefits to millions of resource-poor farm households living in the salt-affected regions.

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Autonomous Adaptation Strategies to Multiple Stressors: A Case Study with Marginal Communities in Eastern Uttar Pradesh, India

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Abstract

Recently, autonomous adaptation strategies have gained momentum for sustaining the livelihoods and strengthening the social-ecological resilience in the face of a rapidly changing multiple stressor environment. This study, conducted in the sodicity-affected parts of Azamgarh district of eastern Uttar Pradesh, India, tries to show how an inextricable interconnection among the traditional social systems, local knowledge, and surrounding environment has been critical to the well-being of indigenous peoples dependent heavily on natural resources. A combination of social-ecological methods including transect walk and site visits through foot-walk and canoeing, event ecology, participant observations, focus group discussions, personal interviews, and data taken from satellite imagery were applied to understand the changing dynamics of *Bhar* community-managed wetland ecosystems on livelihoods and social-ecological resilience. Results indicated that ecological (e.g., high soil pH, seasonal waterlogging) and climatic stressors (e.g., erratic rainfall) imposing livelihood risks to the *Bhar* community are increasingly becoming unbearable due to compounded impacts of socioeconomic (rampant poverty and pervasive land use) and institutional (weak governance and poor reach of formal institutions) stressors. In the past three decades or so, *Badaila* lake area has shrunk considerably with an accompanying increase in soil sodicity making this wetland ecosystem further vulnerable to the external shocks and putting the *Bhar* community livelihoods at risk and compelling them to evolve location-specific autonomous adaptation strategies. These included relying primarily on integrated access to and management of upper (grazing and rice-wheat), middle (rice-wheat, local vegetables, oils, and pulses), and low (cultivating local rice) landscapes as well as acquisition of wetland resources (wild rice *tinni,* fish, etc.) to adapt to these stressors. When livelihood resilience is

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perturbed by the stressors, *Bhar* people often migrate to cities in search of gainful jobs and also become beneficiaries of certain social security schemes to strengthen their livelihoods. This study has implications on maintaining social-ecological resilience of nature-dependent communities living in marginal environments, exposed to multiple stressors, and relying heavily on integrated autonomous adaptation strategies.

Keywords

Bhar community · Autonomous adaptations · Multiple stressors · Integrated land use system · Livelihoods · Social-ecological resilience

30.1 Introduction

About 1.5 billion smallholders, family farmers, and traditional growers cultivating ~350 million small farms (~20% of the world's arable land) produce nearly half of the global agricultural output for domestic consumption (ETC Group 2009; Altieri 1995; Altieri and Nicholls 2013). Most of the food consumed in the world comes from ~5000 domesticated crop varieties grown primarily in diverse subsistence farming systems (Altieri 2001; Altieri and Nicholls 2013). The farmers and local communities living in ecologically stressful and socially disadvantageous environments satisfy their livelihood needs through varied knowledge systems and local strategies (Gupta 1991; Singh et al. 2012; Altieri and Nicholls 2013; Singh et al. 2014a, b). The means and ways instrumental in livelihood adaptations by small and marginal communities are mostly determined by the specific requirements of their complex social-ecological systems (Liu et al. 2007; Berkes et al. 2003; Berkes 2009) and are driven by factors such as access to knowledge networks, common property institutions, and inter- and intra-level household strategies (Richards 1985; Gupta 1990; Agrawal 2008). Communities who live in risky and uncertain environments, perform agriculture with their family labors, and have fragmented entitlement of accessing external and local resources (Pimbert et al. 2001) broadly have three choices for adaptation: access to common property resources (CPR), combined use of CPR and private land resources, and management of private land resources for crop production and animal rearing (Gupta 1990).

World over, only few studies have been conducted for understanding the diversity of small-scale and family managed agricultural systems and informal strategies that millions of small farmers have adapted (Liwenga 2008) to strengthen their livelihoods in the face of multiple stressors (Altieri 1995; Altieri and Toledo 2011; Singh et al. 2012). The multiple evidence-based approach, whereby farmers' knowledge and experiences and scientific knowledge systems are viewed together by multi-stakeholders to generate different manifestations of knowledge (adaptive knowledge), may also generate new insights (Berkes 2009; Weatherhead et al. 2010) and practices through reciprocal learning and complementarities (Altieri 2001; Berkes 2009; Tengo et al. 2014) to provide lasting and efficient solutions to many agricultural problems. Such an approach may further help evaluate the composite knowledge systems and technologies (Berkes 2009) for small farmers and may broaden the understanding to solve problems of small agricultural production systems and natural resources based livelihood strategies (Halwart 2006; Tengo et al. 2014).

Land degradation, defined as the partial or complete loss of soil productivity and the accompanying decline in biodiversity and ecological services, has been a major cause of human misery and social chaos since time immemorial. In the recent decades, factors like heavy soil erosion, depletion of fresh water, and irrigation-induced salinity have emerged as the major drivers of land degradation, dealing a severe blow to the food and livelihood security of a large chunk of global population, especially in marginal and ecologically fragile areas. Relentless salinization of productive croplands is increasingly being seen as a major environmental and food security threat in several parts of the world (Sharma and Singh 2015, 2017). In India, nearly 6.73 million ha (M ha) potentially arable area is either saline (40%) or sodic (60%) (Singh et al. 2010). This study was conducted in Azamgarh district lying in the Eastern Plain zone of Uttar Pradesh (UP) state and characterized by the presence of moderately to strongly sodic soils as evidenced by higher than normal soil exchangeable sodium percentage (ESP >15) (Mandal and Sharma 2006). Farmers in the eastern UP are facing multiple stressors in terms of sodicity, poor adaptive capacity, and restricted access to improved agricultural technologies (O'Brien and Leichenko 2000; O'Brien et al. 2004). This region is well known for its diverse terrestrial and wetland ecosystems instrumental in sustaining multifarious ecological services (Singh et al. 2012) and in providing viable livelihood options to the majority of subsistence farmers (NAAS 2013). Insofar as the problem of sodicity is concerned, preponderance of districts of degraded and low-yielding sodic lands in many districts of eastern Uttar Pradesh (Mandal and Sharma 2006) imposes substantial limitations on soil health and crop harvests, justifying the need for technological interventions to strengthen the adaptive capacity of the affected landholders. It is seen that farmers often employ the traditional ecological knowledge (TEK) based location-specific adaptive practices (often mediated by informal institutions) (Gupta 1995) to adapt to abiotic stressors and productively utilize the natural resources (Singh et al. 2014a, b). Of late, however, sociopolitical distortions and some structural changes in the traditional social institutions are increasingly posing constraints on sodic soil reclamation and management through traditional means (Prakash 2002; Singh et al. 2014a, b). This state of affairs has necessitated timely and appropriate technological interventions to buffer the resource-poor farmers from multiple stressors (MoEF 2012) as well as to further enhance their adaptive capacity under changing socioeconomic and climate scenarios.

The livelihood resilience of a particular social-ecological system can be maintained by applying an integrated approach including conservation strategies (Singh and Singh 2004; Turner and Berkes 2006; Turner and Turner 2007). However, despite considerable attention directed toward such approaches, there has been a limited experimentation on integration of such knowledge systems in adaptation and mitigation policies for marginal environments in India (Turner 2005; Turner and Berkes 2006; Ramakrishnan 2007). To better understand key aspects of autonomous strategy, by taking *Bhar* community as a case study example, we studied their traditional integrated approach for managing the terrestrial and aquatic resources. Keeping these facts in mind, this study was carried out with following objectives: (i) to identify and understand integrated land use production systems and multiple stressors as perceived by *Bhar* community and (ii) assess the adaptation strategies followed by *Bhar* people and identify their willingness to conserve local resources to make their livelihoods resilient.

30.2 Conceptual Framework

According to the Intergovernmental Panel on Climate Change (IPCC 2001), adaptation that does not constitute a conscious response to climatic stimuli but is triggered by the changes in natural systems and by market or welfare changes in human systems is recognized as "autonomous." Autonomous adaptation essentially describes the management of a particular stressor by the local farmers based on their own knowledge, experiences, and resources (Eakin et al. 2013; Singh et al. 2017; Holzkamper 2017). This is increasingly being recognized as the foremost strategy by the resource-poor farmers for managing the ecological and other stressors, especially in areas where agriculture is less developed (Singh et al. 2012, 2017). Although abrupt and extreme climatic events and certain structural changes like those arising due to globalization may make implementation of autonomous adaptation strategies somewhat difficult (Stern 2007), this is still the most dependable strategy for the majority of the marginal and nature-dependent resource-poor communities (Singh et al. 2017). The success of such strategies depends to a great extent on factors like ecological, social, and cultural factors (Agrawal 2008; Thorn et al. 2015). The extent of autonomous adaptation is often altogether different in developed and developing societies characterized by the easily accessible formal knowledge and a week institutional support, respectively. It is seen that poor governance renders people less capable for rendering the external resources, even if they are available (Malik et al. 2010; Westerman et al. 2012). Available evidence suggests that local communities exposed to ecological and climatic stressors have also been trying to conserve natural resources (plant, animals, soil and water) to maintain social-ecological resilience (Alcorn 1997; Westerman et al. 2012; Fisichelli et al. 2016) by applying the autonomous strategies (Thorn et al. 2015). Until quite recently, conservationists and policy makers accorded little credibility to local autonomous practices of land and resource management for livelihoods (Berkes et al. 2000). The past few decades, however, have witnessed a growing recognition of the importance of examining the linkages between social-ecological systems in managing the way natural resources are used (Alcorn 1997; Ostrom 1997; Pretty 2003). Autonomous strategy is often attributed to diversification, mobility, exchange, rationing, pooling, intensification, and applying TEK, among others, to deal with the multiple stressors (Thorton et al. 2010; Thorn et al. 2015). Taking insights from these studies, in this study we considered "autonomous adaptations" as the responses mainly to ecological, climatic, and socioeconomic stressors.

Although few researchers have emphasized the role of integrated farming models for maintaining livelihood security and social-ecological resilience (Dagar 2014; Sharma and Singh 2015), limited empirical studies have been conducted on ecological stressors such as waterlogging, soil and water salinity, and sodicity. Again, scanty information is available on ecologically stressed unique wetland ecosystems and the associated diverse land use systems, often referred to as the "marginal environments" (FAO 2000), and those influencing farmers' livelihood strategies. It is generally considered that such marginal environments are homes to some of the most poor and marginalized sections of the society (Blaikie 1985; Kwaku 1995; Gray and Moseley 2005). Continual degradation of such marginal areas would only further aggravate the poverty, increasing the livelihood risks of vulnerable communities (Kwaku 1995; Gray et al. 2005). In this backdrop, high soil pH-affected lands located in disadvantageous locations (e.g., near lake shores prone to repeated flooding) and currently being owned and managed by the *Bhar* people were treated as the "marginal environments."

Scholars observed that autonomous adaptations applied in an integrated form for conserving the natural resources (Singh et al. 2012; Westerman et al. 2012) may, in turn, improve the livelihood resilience of the local communities (Agrawal 2008; Thornton and Manasfi 2010; Thorn et al. 2015). Social learning and local knowledge networks coupled with the flexibility of communities to move up and down across the landscape may further enhance the livelihood resilience as reported by Tompkins and Adger (2004), Westerman et al. (2012), Marshall and Stokes (2014), and Fisichelli et al. (2016). Insights were taken from these studies to combine the components of autonomous strategies and conservation practices followed by the *Bhar* community to understand as how they can sustain their livelihoods in marginal environments (Chambers and Conway 1992). The purpose was to contextualize integrated adaptation strategies by taking insights from the theories of livelihood and social-ecological resilience (Westerman et al. 2012; Fisichelli et al. 2016). Firstly, a set of major stressors influencing the *Bhar*'s livelihood means including the changes in area of wetland and constraints on upward and downward mobility across the studied wetland ecosystem (*Badaila taal*) were identified. Secondly, we tried to coordinate institutional (presence of formal institutions and their governance) and socioeconomic (land tenure, marginalization, and education) factors to contextualize their multiplicity with stressors. This could help us learn as how strategic adaptations by the *Bhar* community to multiple stressors were helpful in minimizing the crop losses in sodic lands or in waterlogged lowlands where normal cropping is not easily possible.

30.3 Research Methodology

30.3.1 The Study Area

This study was conducted in *Bhar*-dominated villages in the eastern part of Azamgarh district of Uttar Pradesh (UP). The district lies between 25° 38′ and 26° 27′ north latitude and 82° 40′ and 83° 52′ east longitude at an elevation of 64 m asl. This region, having a subhumid climate with most of the precipitation falling between July and August, is endowed with plentiful natural resources – deep soils, good-quality surface and groundwater, and a congenial climate, allowing multiple cropping (Rai 2000). However, soil sodicity is a major edaphic stress in large parts of the district. Integrated farming systems comprising of crops and livestock predominate throughout the study region. Common field crops in the study area include paddy rice, wheat, barley, sugarcane, potato, maize, red gram, chickpea, black gram, and green gram. Perennial tree fruits and vegetables also occupy a sizeable area. The *Bhar* community, with whom this study was conducted, is well known for its distinctive lifestyle, relying heavily on freshwater aquatic resources (wild rice, fishes, horticultural produce, etc.). The lands where they grow crops are sodic in nature and less productive (1.8–2.2 t/ha rice; 1.5–2.0 t/ha wheat), compelling them to harness the aquatic resources (Dugan et al. 2002; DEFRA 2005; Kumar and Yashiro 2013) as well as accessing other land use systems for their livelihood support from other land use systems (Fig. 30.1). However, of late, global changes have shifted the

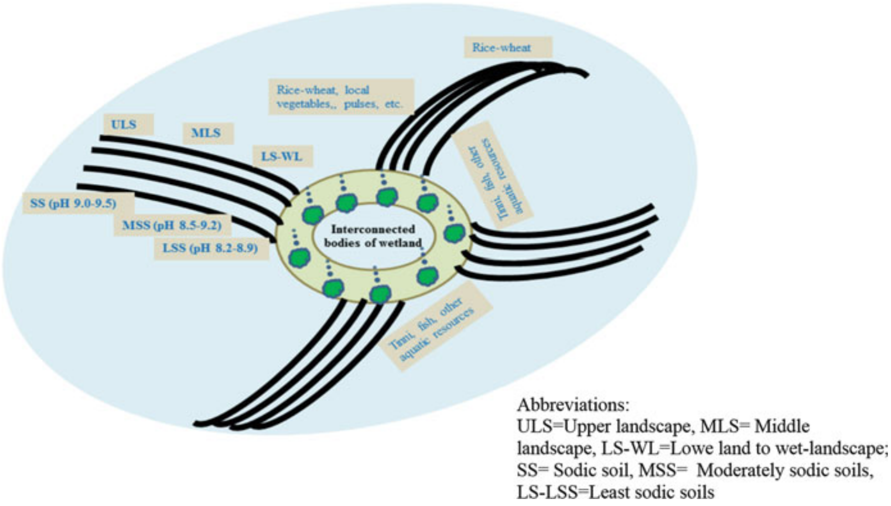


Fig. 30.1 Temporal and integrated land use systems accessed by *Bhar* community for the livelihood adaptation. (Source: Own creation. Abbreviations: *ULS* upper landscape, *MLS* middle landscape, *LS-WL* lowe land to wet-landscape, *SS* sodic soil, *MSS* moderately sodic soils, *LS-LSS* least sodic soils)

focus of this community toward other means of livelihoods (migration, availing policy benefits such as public distribution system, etc.).

30.3.2 Approach of Study

This study was conducted using both qualitative and quantitative approaches with multiple methods (Kaplowitz 2000). Five *Bhar*-dominated villages were selected purposively based on their population. From each village, ten farmers (total 50) were identified as the respondents using snowball sampling technique. The average age of respondents was 60 years, and they had 25–40 years of experience in agriculture and accessing wetland resources. While selecting the individuals for the study, only those permanently residing in the village and depending solely on integrated land use systems (terrestrial and wetland) for bread and butter with at least one of the land uses being "sodic" were chosen. A total of 15 key participants (~ 3 from each village) were also selected who helped in organizing the focus group discussions (FGD) in their respective villages and offered their expertise during transect walk in and around the *Badaila taal* (lake). This allowed the gathering of first-hand information on *in situ* management and the access patterns of the wetland resources. Visits were also made to the sodic fields where crops are grown. During the transect walks, discussions on aspects like stressors associated with a particular land use system, general adaptation strategies, and the access to aquatic resources took place. In addition, habitat descriptions and biophysical attributes of lands and water bodies, making a complete structure of *Badalila taal*, were elaborated. The FGD allowed us to obtain a general qualitative overview (Morgan 1997) of the historical background relating to common property resource (CPR) management of the *Badaila taal*, access to it, and crop production in the adjoining edges (*cf*: Chambers 1992; Ashenafi and Leader-Williams 2005). Discussions with the community elders helped understand spatial variations in the land use systems (e.g., up and mid landscape affected by sodicity, fertile lands adjoining to *Badaila taal*, and wetlands) and the relative dependence of local people on a particular land use system. A total of 50 selected *Bhar* community members were interviewed in order to quantify their perceptions on multiple stressors, adaptation strategies, and willingness on conservation of wetland resources.

Initially, we documented a list of wetland resources, primarily the local species of fish, wild rice *tinni* (*Oryza rufipogon*), and horticultural resources [*kaul-gatta* (*Nelumbo nucifera*), root and leafy vegetables, etc.] with the key informants to understand the general patterns in their use and the current conservation status (Singh et al. 2012). This knowledge was further enriched through fishing and canoeing to harvest *kaul-gatta* with *Bhar* people (participant observation). During this exercise, fish diversity was observed during the rainy season, and live specimen was also collected to identify them. Local names and attributes of the collected fish species were confirmed by discussions with the elderly (professional) fishermen of the *Bhar* community and were further cross-checked by discussions with fishery expert at ICAR-Central Soil Salinity Research Institute, Karnal. Event ecology method was applied to learn the past climatic and ecological events affecting *Bhar*'s livelihood. Continuous observations of *Badaila taal* ecosystem and land tenure changes (especially in common property resources) were made for 5 years (2013–2017) during the harvesting/growing seasons of wetland resources (during April to October) and crops (during November to January).

30.3.3 Measurement of Variables

The content for developing interview schedule on perceived stressors was collected from review of local literature (newspapers, magazines, relevant websites and research articles) and field visits held with the *Bhar* community. Perception about multiple stressors was measured on five five-point continuum as "strongly agree (SA)," "agree (A)," "undecided (UD)," "disagree (DA)," and "strongly disagree (SDA)" by applying Likert scale with scoring technique 5 to 1 (Edwards 1969). The adaptation and conservation strategies were measured using four-point continuum as "high," "moderate," "least," and "nil" for which scores 3 to 0 was assigned. Quantitative data on perceived stressors, adaptation strategies, and willingness for conservation of selected wetland resources were generated using statements. For example, following statements (indicative) were applied: (i) edaphic (high soil pH) factors causes stress on your livelihood (stressor): SA (5), A (4), UD (3), DA (2), SDA (1); (ii) you grow rice and wheat in upper landscapes where sodicity is more (adaptation) yes/no: If yes, then how much, higher (3), moderate (2), low (1), nil (0); and (iii) will you conserve wild rice *tinni* (*Oryza rufipogon*) for maintaining the current and future resilience of ecosystems and own livelihoods (emphasis on conservation)? Yes/no, if yes, then how much? higher (3), moderate (2), low (1), nil (0). Among the wetland resources, we selected three most widely used resources which contribute substantially to livelihoods, i.e., local fish, *tinni*, and *kaul-gatta*, as part of knowing *Bhar*'s willingness on conservation of wetland resources. This was done with a view to integrate them with the analysis of currently applied autonomous adaptive practices in minimizing the livelihood risks (*increasing resilience*). The open-ended questions were inserted in interviews schedule covering TEK, access patterns, and institutional perspectives (CPR and private resources) on wetland resources and sociocultural and livelihood values of different land use resources (qualitative aspects).

The real-time data on changes in the total area of lake, water streams, and salt-affected soil patches were taken through GIS tools to assess their relative contributions in impacting the livelihoods of and adaptation strategies by the *Bhar* community. The calculation of salt (sodicity)-affected land was done using Landsat series datasets for the period of 1980 and 2017 by using red and green bands. In this study, satellite imageries of the May month were obtained from the USGS (United State Geological Survey) (USGS 2018). The aim of this exercise was to delineate the temporal changes taking place in the sodicity-affected area in and around the *Badaila* lake. The normalized difference salinity index (NDSI) using the formula $\mathrm{SI} = \sqrt{GXR}$ (where G= green band, R= red band) was applied to estimate the salt (sodic)-affected land area (Douaoui et al. 2006). This equation was supported by red and green bands to find out the changes in sodic patches. The temporal changes in area of *Badaila taal* detection were done using supervised classification technique applied on Landsat datasets for the post monsoon period from 1984, 1994, 2004, and 2014 (~ 30 years). The percentage change pattern in water streams was delineated by using ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) digital elevation model of resolution 30 meters (USDI 2018) by applying hydrology tool (Venkatachalam et al. 2001).

30.3.4 Data Analysis

Soil samples were taken from different land use systems, and pH was diagnosed using standard laboratory techniques at ICAR-CSSRI Karnal. Qualitative data were explained using explanatory research design. The quantitative data in terms of scores generated on perceived stressors, adaptation, and willingness of conserving selected wetland resources (local fishes, *tinni*, and *kaul-gatta*), as component of livelihood resilience, were analyzed using Wilcoxon matched-pairs signed rank test. The data on intercorrelation among these variables were analyzed using Spearman correlation test with the help of STAR statistical packages (version 2.0.1) (IRRI 2013) to draw the inference from this study.

30.4 Results

30.4.1 Integrated Land Use Systems and Their Associated Stressors

The results indicated that broadly there are three types of land use system which are integral in nature (Fig. 30.1 and Table 30.1). Each land use system is exposed to a set of ecological (soil sodicity and poor soil fertility) and climatic (drought and flood) stressors which in interaction with sociopolitical and institutional factors render *Bhar* community vulnerable to external shocks. *Bhar* farmers not only have less adaptive capacity (small land holdings, less education, and poverty) but also face problems caused by the poor presence of formal institutions and the services they provide (formal knowledge, scientific technology, and crop inputs) to stabilize agricultural production in marginal environments. Data presented in Table 30.2 on overall perceived stressors indicated that climatic, socioeconomic, and political (poor presence of institutions and governance in enabling adaptations) stresses had an equal impact on *Bhar*'s livelihoods with Wilcoxon matched-pairs signed ranks test validating their significance level (Table 30.2).

Further analysis using Spearman's rank correlation indicated that poor governance of formal institutions (formulation of policies on natural resources and their governance) may influence the changes in land tenure (*top-bottom* approach on wetland resources management) significantly. With increase in climate variability, the land tenureship is likely to negatively change (Table 30.3). The poor economic

Table 30.1 Seasonal pattern of access to resources across the landscapes and the associated stressors[1]

Seasons	Upper landscape[2]		Middle landscape		Lower landscape to wetland	
	Crops resources	Stressors	Crop resources	Stressors	Wild resources	Stressors
Rabi	Local wheat varieties.	Higher soil pH (8.9–9.8), meagre investments, poor formal knowledge network, poor agricultural governance and climate variability	Wheat, pea, gram, sugarcane and local vegetables.	Soil pH(8.5–9.0), tiny landholding making unable to adopt mechanization, low resource use capacity, climate variability	Wild rice with indigenous fishes and aquatic plant resources.	Drought, flood, land tenure issue, *top-bottom* governance issues on common property resources, encroachment, and changes in wetland areas
	Yield: 1.8–2.2 t/ha rice, 1.5–2.0 t/ha wheat		Yield: 2.0–2.5 t/ha rice, 1.8–2.1 t/ha wheat		Yield: 2.2–3.2 t/ha rice (local rice ~1.8 t/ha), 2.2–3.0 t/ha wheat	
Kharif	Rice crop with local varieties	As above	Rice crop with local varieties (*lohatan*)		Access of seasonal fish and aquatic plant resources	As above
Zayad	No crop	As above	No crop		Micro-ecosystem being used for rice nursery and carrying fertile clay for upper landscape	As above

[1] Data pertaining to this table was generated using FGD (focus group discussion) with 15 key participants. [2] Here landscape is a relative term and is applied in context of comparing the land use systems across the gradient.

Table 30.2 Prioritization of perceived stressors of *Bhar* farmers with Wilcoxon matched-pairs signed rank test

Perceived stressors	Ranks based on total score	Statistics	Significance P > V	Priority group
Edaphic (soil pH)	1	–	–	1
Land tenure	2	333.00	0.258^{ns}	1
Climate variability	3	300.50	0.357^{ns}	1
Low economic status	4	244.00	0.406 ^{ns}	1
Poor governance of formal institutions	5	210.50	0.433 ^{ns}	1
Poor institutional presence	6	167.50	0.449 ^{ns}	1
Small land holdings	7	294.00	0.279 ^{ns}	1
Lack of required inputs (salt-tolerant seed and gypsum)	8	188.50	0.370 ^{ns}	1
Changes in land use pattern	9	289.00	0.439 ^{ns}	1
Low educational status	10	281.50	0.481 ^{ns}	1
Social marginalization	11	290.50	0.195 ^{ns}	1

ns non-significant

status of farmers was significantly associated with the presence and poor governance of formal institutions while negatively correlated with the social marginalization. The low educational status of farmers hindered them from accessing required inputs in the time of needs (salt-tolerant seed and gypsum for high sodic soils and contingency measures during drought and flood) (Table 30.3). The intercorrelations among different variables decide the degree of perceived risks to the livelihood resilience of *Bhar* farmers. The combination of digital elevation model and satellite imagery data indicated that during 1980, 1642.32 ha land was affected by sodicity (ground-truthing was done for soil sodicity) which increased to 1862.73 ha in 2017 (Fig. 30.2). Thus, there was increase of about 220 ha in the sodic land area in a span of about three decades in 5 km radius from the shore of *Badaila taal* (lake). The elevation model revealed that most of the salt accumulation took place in the lower elevation area, i.e., Southeast and to a little extent in Southwest parts of *Badaila* lake from where some of the contributory streams also pass.

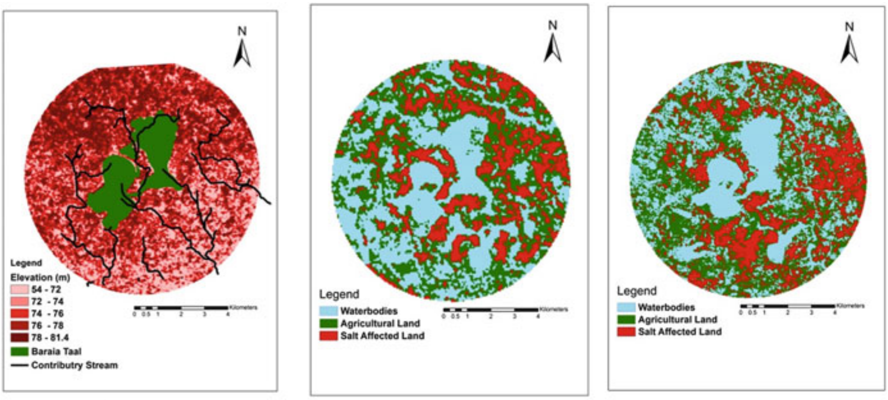
30.4.2 Changes in Wetland Ecosystem

While assessing the changes in wetland ecosystem (i.e., *Badaila taal*), we treated the area of the lake and water stream(s) as two variables. Our analysis through satellite imagery on major streams (contributory lines and natural drains) contributing to hydrology of *Badaila taal* indicated that there has been a dramatic reduction in its size (total area) by 94.54% in the past two decades (1995–2015) (Table 30.4). Such a drastic reduction in the stream size can spell doom for the existence of *Badaila taal*, because water flow and volume in these stream(s) are inextricably linked to the overall lake ecosystem health and sustainability. Further, the total area of *Badaila*

Table 30.3 Association between perceived stressors (Spearman's rank correlation)

Variables	Land tenure	Climate variability	Poor economic status	Poor governance	Poor institutional presence	Small land holdings	Lack of required inputs	Changes in land use pattern	Low education	Social marginalization
Edaphic (soil pH)	−0.222	−0.136	0.109	−0.223	0.025	−0.070	−0.135	0.005	0.017	−0.126
Land tenure		-0.269^{*}	−0.017	0.382^{***}	−0.177	−0.062	0.113	−0.122	0.043	−0.228
Climate variability			−0.066	−0.051	−0.110	0.229	−0.102	0.197	0.077	0.229
Low economic status				0.015	0.233^{*}	−0.208	−0.007	0.026	−0.152	-0.309^{**}
Poor governance of formal institutions					0.330^{**}	−0.025	−0.051	−0.144	0.030	−0.092
Poor institutional presence						0.092	−0.100	0.027	−0.039	−0.048
Small land holdings							−0.084	−0.001	−0.083	0.200
Lack of required inputs (salt-tolerant seed and gypsum)								−0.212	0.294^{**}	−0.101
Changes in land use pattern									−0.116	0.216
Low educational status										0.074

*Significant at 0.10 level of significance; **Significant at 0.05 level of significance; ***Significant at 0.01 level of significance



(A) Digital elevation model (B) Salt affected area (1980) (C) Salt affected area (2017)

Year	Area in ha	% change in Area
1980	1642.32	0
2017	1862.73	13.4

Fig. 30.2 Map indicating approximate land (ha) affected by sodicity in study area (1980 to 2017). (Source: Own analysis from referred sources)

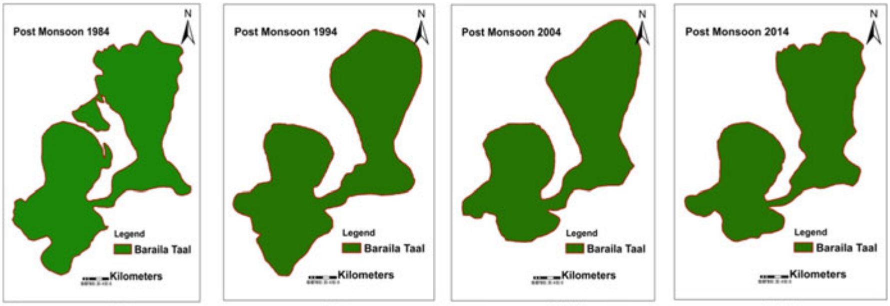
Table 30.4 Temporal change in area of water stream(s) contributing to *Badaila taal* and natural drains flowing from it

	Periods	
Year	1995	2015
Area (ha)	42.6047	2.326
Percent area	100	5.459
% of change	00.00	94.540

Source: Own analysis from referred sources

taal reduced from 91360 ha in 1984 to 89277 ha in 1994 (2.28% reduction) and further to 86685 ha in 2004 (5.12% reduction) (Fig. 30.3). In 2014, continued shrinkage attained alarming proportions with total lake area decreasing from 91360 to 77950 ha, thus a total reduction of about 15%.

During the 1990s, the water streams interconnected to the *Badaila taal* (lake) were essentially a lifeline for the local farmers, especially those whose crop fields were located along these stream(s). In years of early monsoon withdrawal, farmers were able to irrigate rice crop (late variety) at least twice using the water from these natural drains. In most of such years, drain water would also ensure lifesaving irrigations in the wheat crop as well. Most of the respondents reported that supplemental irrigation of rice and wheat crops using natural drain water was no longer possible though evidently attributable to the virtual disappearance of such streams due to encroachment and/or sever erosion in the drain embankment area. This has also considerably reduced water storage in the main lake, adversely impacting the flow of downward streams and reduction in fish diversity: over half of the common fish species (n=20) are no longer found in the lake waters. Besides the main lake, natural drains were the second major fishing ground not only for the *Bhar* but also for other resource-poor farmers who grew rice in the low-lying sodic areas. The



Year	1984	1994	2004	2014
Area (in ha)	91360	89277	86685	77950
% change	00.00	2.28	5.12	14.68

Fig. 30.3 Temporal changes in area of *Badaila taal* (1984 to 2014). (Source: Own analysis from referred sources)

upward and downward water streams were major connecting lines to all the small ponds located within 8–10 km radius of the lake which served as the breeding grounds for the fish.

30.4.3 Adaptation Strategies

30.4.3.1 Access of Wetland Indigenous Resources

Functioning and evolution of aquaculture and wetland ecology are affected by many factors with human accessibility and conservation strategies playing the major roles (Dugan et al. 2002). This ecosystem is one of the most productive natural resource for the survival of resource-poor people (Kinch 1999). It is true in much of the study areas that resources use from the *Badaila taal* (lake) and interconnected ponds and natural drains provide subsistence needs as well as some income to *Bhar*. A variety of resources available from wetland ecosystem are presented in Table 30.5. Results revealed that local fish (45.0%) followed by wild rice *tinni* (40.0%) and *kaul-gatta* (36.0%) are major wetland resources being accessed to sustain the subsistence livelihoods. The fish species, namely, *sidhari* and *chelhwa* [(*Oxygaster bacaila*) (Ham.)] (available from August to September), *goinjee* [(*Macrognathus aculeatum*) (Bl.)], *tengna* [(*Mystus vittatus*) (Bl.)], *padhina* [(*Wallago attu*) (Schn.)], *sour*, *chanaga* [(*Channa gachua*) (Ham.)], *girayi*, *Basanguti* [(*Ailia coilia*) (Ham.)], *bhutti* [(*Eutropiichthys murius*) (Bl.)], *singhi* [(*Heteropneustes fossilis*) (Bl.)], *bam* [(*Muraenesox cinereus*) (Forsk.)], and *mangur* [(*Sphyrna blochi*) (C.)] (available from October to April), are considered best local fish in terms of taste and quality. To sustain these species in CPR, fishing area is determined by the community elders taking into account the factors like season, climatic conditions, and land tenure system. During the breeding season, fishermen tend to be hesitant in fishing.

Some other major provisioning services of the studied wetland include grasses for animal gazing, leafy and root vegetables, water for protective irrigation in rice and wheat, and as a buffer minimizing the flood hazard (*regulatory service*) (Table 30.5).

Table 30.5 Access of wetland resources by the *Bhar* community in sustaining the subsistence livelihoods

Indigenous resources	% of use by community members*
Local fish and other animals (crab, shrimp, snails)	45.00
Wild rice *tinni*	40.00
Kaul-gatta fruits (nelumbo)	36.00
Grasses for animal grazing	35.00
Leafy and root vegetables (*karemua* and *bhansid*)	32.00
Water used in irrigation	25.00
Act as buffer for flood control	22.0
Ash after burning the grasses	20.00
Lake soil use	20.00
Mustard and early chick pea cultivation in unutilized stretches	15.00
Root vegetables	8.00

*Multiple percentages

The *narai* grass (*Scirpus grossus*) found naturally in the lake is a valuable source of organic matter. While green stems are used as fodder during the lean period (October and November), ash from the dried stems is applied in wheat fields as a source of nutrients/soil conditioner. In the last few years, *Bhar* people have started selling some of the aquatic resources like local fish, *kaul-gatta*, *bhansid*, (root of *kaul-gatta* as vegetable), and *karemua* (*Ipomoea aquatica*) as leafy vegetables on the local markets for generating additional incomes. Contrarily, *Bhar* peoples living far away from the *Badaila* lake depend on other means like subsistence farming and sale of the fish purchased from their counterparts residing near the lake.

For paddy growers around the *Badaila taal* (lowland to wetland area), it is a customary practice to apply the lake silt (decomposed clayey organic material) to sodic lands (middle to upper landscape) during the dry period. By doing so, farmers have been able to reduce the fertilizer costs by about 10% and increase the crop yields by about 5–8%. During the monsoon season, lakeshore (micro-ecosystem) is used for raising the rice nursery for transplanting in the sodic lands. This practice is believed to harden off the rice seedlings such that they would endure sodicity and climatic shocks in the main field. During the *Rabi* season (October to March), small farmers judiciously utilize the pond and small lake dykes for growing mustard and chick pea crops. During the rainy season, about 1-m-high bunds are constructed around the upland fields least affected by the floods, to allow the inflow of organic matter rich from high elevations for growing late maturing rice varieties. Simultaneously, at an appropriate point, the bund is cut to make an outlet for the entry of local fish in the paddy fields which are caught in the first week of October for sale on local market.

Depending on the distance from the lake, we observed considerable differences in the monetary value of lands. *Bhar* people accord a high priority to the lands in the immediate vicinity of lake with their prices ranging from INR 200,000 to 250,000 ha^{-1}. In contrast, non-*Bhar* community members treat such lands

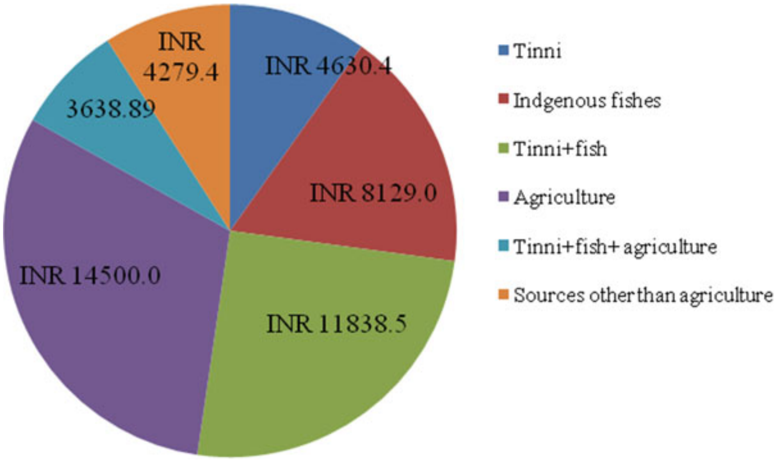


Fig. 30.4 Contribution of household income generated from access of diverse land use resources. (Source: Own analysis)

troublesome including the constraints imposed by soil sodicity and thus warranting better management. It is due to this reason that they are unwilling to pay hefty prices for such lands. While assessing the component-wise contribution to the total incomes, we found integrated *tinni* rice-fish culture to be the major contributor to (INR 11838.0) (Fig. 30.4) the household economy of the *Bhar* community. Although crop cultivation in upper to middle landscapes with soil sodicity varying between pH 8.6 and 9.8 ensures food security, it contributed little to the total income. Particularly in drought, crop cultivation in upland becomes difficult due to the higher sodicity or climate extremes. During this period, farmers try to uplift water for irrigation from wetland area, but due to low facilities, this practice becomes difficult for economically poor farmers.

To accession patterns of common wild rice (*tinni*), fish and other wetland resources vary from place to place. Other communities in the same area consider fish resources to be a common property, while in *Bhar* community, in few places, they are entitled for fishing in *Badaila taal* due to its category of CPR. On the other hand, few *Bhar* families have acquired fishing rights over a particular area either through the oral consent of or by entering into lease agreements with the Village Panchayat. In recent past, due to change in land tenure, access of fishing waters has become difficult due to the involvement of commercial contractors represented by the Village Panchayat and also posing threat to aquatic biodiversity. Although *Bhar* are exposed to such stressors, the comprehensive strategies of accessing wetland ecosystems together with agricultural systems enable them to spread the livelihood risks to some extent.

30.4.3.2 Autonomous Adaptation Strategies Against Perceived Stressors

The studied farmers are socioeconomically marginal having small land holdings and less adaptive capacity making them highly vulnerable to the multiple stressors. This

Fig. 30.5 *Lohatan* rice planted in low landscape in *Badaila taal (harvested in October last)*. (Photo: Ranjay K. Singh)

situation compels them to develop location-specific autonomous strategies for different seasons (*Rabi*, *Kharif* and *Zayad*). They combine resources from diverse land use systems including upper (rice-wheat system), middle (rice-wheat system with local vegetables, pulses and oil seeds) and low (wet) landscapes (Table 30.1). The extent and amount of resource accession from such diverse land use systems usually varies with farmers' own resources and the weather patterns in a particular year. For example, in drought years, joint *Bhar* families tend to increase the area under mustard and pulses in fertile soils having residual moisture in dry wetland areas during *Rabi* season. Farmers having small land holdings try to acquire lands in the wetland areas after consulting large farmers who often keep their wetlands fallow to avoid the crop failures. Sometimes large farmers with nuclear family lack the labor, and most often they rent their land on share basis to *Bhar* farmers. *Bhar* community also cultivate local rice called *lohatan* (well adaptive in flood condition, Fig. 30.5) in low-lying areas prone to flood, and in combination they have access to local fish, wild rice (*tinni*) (Fig. 30.6), and other aquatic resources such as *kaul-gatta* (Figs. 30.7 and 30.8).

Data presented in Table 30.5 indicated that *Bhar* farmers accorded the top priority to rear and catch the indigenous fish from wetlands (*adaptation*), growing crops in middle (rice-wheat with local vegetables, pulses, and oil seeds) and upper (growing rice and wheat) landscapes as autonomous adaptation strategies to make their livelihoods resilient. Availing the benefits under schemes such as MGNREGA (Mahatma Gandhi National Rural Employment Guarantee Act) and PDS (Public Distribution System) as *adaptation*, willingness to *conserve* wetland resources such as *kaul-gatta*, access of *tinni* alone, cyclic migration to cities and towns, and accessing *tinni* together with local fish (as *adaptation*) were found to be of secondary priorities for adaptation to the perceived stressors (Table 30.6). To make livelihoods and agro-ecosystems even more resilient, farmers showed willingness to conserve *tinni* as the third priority. The Spearman's rank correlation revealed that *tinni* wetlands were likely to have the abundance of local fish, adding to the livelihood

Fig. 30.6 *A view of tinni* rice (*Oryza rufipogon*) in *Badaila taal* getting ready to harvest in October month. (Photo: Ranjay K. Singh)

Fig. 30.7 *Kaul-gatta* (*Nymphaea*) ready for harvest in *Badaila taal*. (Photo: Ranjay K. Singh)

resilience of the *tinni* growers (Table 30.7). Cultivation of crops (rice and wheat) in upland sodic soils was found to be positively and significantly associated with the access of aquatic resources (*kaul-gatta* and *tinni*). An interesting correlation was seen between decreased cyclic migration (*autonomous*) and availing benefits (*planned*) under policies such as MGNREGA and PDS. The willingness for conservation of the aquatic resources (e.g., *kaul-gatta*) for generating extra incomes depended to a great extent on its current access patterns.

The intercorrelations among the perceived stressors, adaptation, and conservation strategies revealed that changing land tenure (*stress*) was positively associated with willingness to conserve the aquatic resources (e.g., *kaul-gatta*) (Table 30.8). The

Fig. 30.8 Kaul-gatta: *Berwa* (*Nymphaea*) being harvested from *Badaila taal*. (Photo: Ranjay K. Singh)

Table 30.6 Prioritization of autonomous adaptation strategies among *Bhar* farmers with Wilcoxon matched-pairs signed rank test

Adaptations	Ranks based on total score	Statistics	Significance P > V	Priority group
Willingness to conserve indigenous fish[1]	1	-	-	**1**
Using wetland indigenous fish[2]	2	234.00	0.124 ^{ns}	**1**
Growing crops in mid-landscape (rice-wheat with local vegetables)[2]	3	116.50	0.493 ^{ns}	**1**
Growing rice and wheat in uplands[2]	4	257.00	0.184 ^{ns}	**1**
Availing benefits under planned schemes (MGNREGA and PDS) [2]	5	367.00	0.019*	**2**
Willingness to conserve other aquatic resources (e.g., *Kaul-gatta*)[1]	6	151.50	0.338 ^{ns}	**2**
Currently accessing other aquatic resources (*kaul-gatta*)[2]	7	357.00	0.127 ^{ns}	**2**
Access of wild rice tinni[2]	8	382.50	0.199 ^{ns}	**2**
Following cyclic migration[2]	9	240.00	0.440 ^{ns}	**2**
Accessing *tinni* with local fish[2]	10	309.50	0.295 ^{ns}	**2**
Willingness to conserve *tinni*[1]	11	668.00	0.000**	**3**

[1] Emphasis on conservation to strengthen current and future adaptation; [2] Emphasis on current autonomous adaption practice.

*Significant at 0.05 level of significance; ** Significant at 0.01 level of significance

MGNREGA Mahatma Gandhi National Rural Employment Guarantee Act

PDS = Public Distribution System

Table 30.7 Association between adaptations practices (Spearman's rank correlation)

Variables	Access of fish	Growing crops in midland	Growing crops in upland	Availing planned schemes	Willingness to conserve aquatic resources[1]	Access of aquatic resources	Access of *tinni*	Cyclic migration	Access of *tinni* and fishes	Conserving *tinni*[1]
Fish conservation[1]	−0.036	0.120	0.010	0.194	0.148	−0.045	0.324**	−0.192	−0.121	−0.026
Access of wetland fish[2]		0.110	−0.035	0.172	−0.024	−0.162	−0.133	0.006	0.006	−0.174
Crops in midland[2]			−0.003	0.000	0.136	−0.120	0.112	0.004	0.128	−0.001
Crops in upland[2]				−0.051	−0.084	0.310**	0.284**	−0.115	0.065	0.175
Availing planned schemes[2]					0.090	0.038	0.061	−0.242*	−0.202	0.027
Conserving other aquatic resources[1]						0.237*	−0.018	0.065	−0.033	−0.043
Access of other aquatic resources[2]							0.031	−0.024	−0.017	−0.111
Access of wild rice (*Tinni*)[2]								−0.040	−0.222	0.038
Cyclic migration[2]									−0.066	−0.112
Accessing *tinni* with fish[2]										0.028

*Significant at 0.10 level of significance; **Significant at 0.05 level of significance; [1] Emphasis on conservation; [2] Emphasis on adaptation

Table 30.8 Association between perceived stressors and adaptations strategies (Spearman's rank correlation)

Perceived stressors	Adaptation strategies										
	Fish conservation[1]	Access of fish	Crops in midland	Crops in upland	Availing planned schemes	Conservation of other aquatic resources[1]	Access of other aquatic resources	Access of *tinni*	Cyclic migration	Access of *tinni* with fish	*Tinni* conservation[1]
Edaphic (high soil pH)	−0.231	−0.007	−0.122	−0.173	0.156	0.000	0.146	−0.025	−0.038	−0.173	−0.009
Land tenure (reduced access from CPR)	0.065	0.092	−0.084	0.188	0.087	0.343^{**}	0.114	−0.040	0.019	−0.083	0.134
Climate variability	0.038	−0.094	0.048	-0.256^{*}	−0.045	−0.068	0.013	−0.088	0.042	0.106	0.222
Poor economic status	−0.021	−0.097	−0.206	0.048	0.043	−0.163	0.100	0.185	−0.074	−0.055	−0.186
Poor governance	−0.125	−0.136	0.070	0.090	0.145	0.003	0.078	-0.233^{*}	−0.038	−0.003	−0.085
Poor reach of formal institutions	0.086	-0.323^{**}	0.053	−0.056	0.190	0.023	0.025	0.046	−0.007	0.151	−0.223
Small land holdings	0.068	-0.299^{**}	0.062	0.058	−0.159	0.139	0.168	−0.005	0.109	−0.064	0.077
Lack of required inputs (salt-tolerant seed and gypsum)	0.077	−0.026	-0.257^{*}	0.342^{**}	0.160	−0.046	−0.037	0.028	−0.083	−0.208	0.280^{**}
Changes in land use pattern	0.080	−0.029	−0.127	−0.104	−0.068	−0.132	0.194	0.057	0.055	0.003	−0.133
Low education	0.046	−0.191	-0.319^{**}	−0.118	0.160	0.030	−0.119	0.089	−0.187	−0.095	0.273^{**}
Social marginalization	0.066	-0.326^{**}	−0.018	-0.231^{*}	-0.405^{***}	0.030	−0.126	−0.137	−0.027	0.036	−0.090

*Significant at 0.10 level of significance; **Significant at 0.05 level of significance; ***Significant at 0.01 level of significance

[1] Emphasis on conservation; [2] Emphasis on adaptation

CPR = Common Property Resources

increased climatic aberration (*stress*) may negatively affect rice and wheat cultivation in upland sodic areas (*adaptation*). The changes in governance regime from *bottom-up* (earlier more village level governance through informal institutions) to the *top-bottom* on *Badaila taal* were found to be negatively associated with the access of *tinni*. Due to poor reach of formal institutions to the *Bhar* community and their small land holdings, the willingness for conserving fish in wetland ecosystems was somewhat negative. It may be due to lack of awareness and motivation. Lack of required inputs on time for coping up with the climatic and ecological stressors was observed to adversely impact the continuance of rice and wheat crops in upland areas. However, farmers were willing to conserve the *tinni* rice (*significantly*) to reduce risks posed by the crop failures in sodicity-affected uplands. With less education (impact decision on adaptive measures), farmers were inclined more to harvest *tinni* rice by reducing the crop cultivation in moderately sodic middle landscapes. Whereas, the social marginality of *Bhar* community was observed to be significantly associated with less capacity of accessing policy-driven resources, difficulty in cultivating crops in upland area, and poor access of fish from wetlands due to changes in land tenures (Table 30.8).

30.5 Discussion

The objective of this study was to identify and understand the integrated land use production systems practiced by the *Bhar* community of eastern Uttar Pradesh, and different stressors impacting their livelihoods. Secondly, we also assessed the diverse but integrated autonomous adaptation strategies against perceived stressors. It was found that *Bhar* people depend more on local adaptive practices governed by the access to and intent of conserving local resources. The key results indicated that there were three major land use production systems, viz., uplands, midlands, and partially to completely wet lowlands, with each land use system facing specific stresses. For example, while soil pH was the major constraint in upper (8.9 to 9.8) and middle landscapes (8.5. to 9.0), extended waterlogging was the main concern in lowland areas where *Bhar* farmers mostly cultivate indigenous rice (*lohatan*) and rear local fish. Other than such ecological stressors, climatic, socioeconomic (less education and small land holdings), and political (poor presence of institutions and governance in enabling adaptations) stressors also played an equal role in impacting their livelihoods. As reported elsewhere (Bunce et al. 2009; McDowell and Hess 2012), perception of resource-poor and marginalized farmers toward the livelihood risks is influenced by a number of factors. The stress caused by one factor may further aggravate the stress imposed by the other factors (*cf:* McDowell and Hess 2012).

There has been steady and alarming reduction in the upward and downward streams contributing to the sustainability of *Badaila taal* (lake) ecosystem. One possible reason behind reduced water flow in these streams is the congestion of natural drains by road and building constructions. Another reason might be increasing encroachment and neglect of the damage to embankments (*cf:* Gupta et al. 2013).

Other reasons could be the hydrological changes caused by climatic factors. The rapid erosion of embarkment of these water streams could also be due to the rapid erosion and damage because soil used in making the embarked lines are sodic in nature and thus prone to dispsersal by the intense rains (Gupta et al. 2013). The spatial changes and reduction in *Badaila* lake by over 14.0% in the past 30 years might ultimately put this ecosystem and its provisioning services at stake. Increase in the sodicity-affected patches by 13.4% during 1980 to 2017 could be due to the changes in water streams and the shrinking wetland area. Reduced water flow have supposedly accelerated water recession and simultaneously increased the run-off from uplands, adding more salts eventually developing into white (sodic) patches in and around the wetland (Sentís 2014). In the integrated land use system, the role of wetland resources was found to be the most significant, and therefore any adverse impacts on *Badaila* lake will pose direct threats not only to the livelihood resilience of *Bhar* community but also to its several regulatory (flood control and climate risks) and supporting services (soil fertility, water quality, energy flow, and local hydrology). Maltby and Acreman (2011) and Bhatta et al. (2016) reported that ecological changes and anthropogenic factors impair the ecosystem services of wetlands, adversely affecting the livelihoods of people dependent on them.

As the *Bhar* people reported, hydrological changes in water bodies and streams and damage to the natural drains had a debilitating impact on indigenous fish species with their numbers reducing from 17–20 to only 5–6 currently, reflecting an alarming rate of biodiversity depletion. Consequently, they have been facing considerable reductions in the harvest of fish and other aquatic resources. The plausible reasons for these hydrological changes include the developmental works (roads, buildings, etc.) by the Village Panchayat and the state government, changes in the land use pattern, and other similar factors (*cf:* Gupta et al. 2013). Changes in water flow and availability in the up- and downstream parts have reduced irrigating water availability for rice and wheat crops during extended dry periods and droughts. These results are in agreement with the findings of Maltby and Acreman (2011) who observed that alterations in the natural drains and hydrology may cause dramatic reductions in aquatic biodiversity and other ecosystem services. The water obtained from *Badaila* lake was considered to be nourishing for crops and as an effective conditioner for the sodic soils. Accordingly, an informal institution called "*sajha*" was formed to ensure equitable sharing of lake water among the community members. Changes in stream flow and lake area are also seen as the major drivers, among others, for the erosion of "*sajha*" system (Singh et al. 2014a, b). These points underscore the need for understanding the complex interactions among the local farmers, habitats, and resource access patterns to draw viable plans for sustainably managing the social-ecological systems (Dressela et al. 2018).

In order to make their livelihoods resilient, *Bhar* respondents showed a strong willingness to align the conservation strategies for aquatic resources with traditional crop husbandry practices for sustained provisioning of diverse services. By adopting a diversified portfolio, they could spread the risks in crop production in marginal environments (*cf:* Marschke and Berkes 2006.). These findings are in line with the arguments of Hoang et al. (2014) who insisted that developing country farmers accessing resources from a range of on-farm and non-farm options were likely to have resilient livelihoods than those depending on a single source. FAO (2007) recommended that in view of the stressors imposed by various factors, integrated crop-fish culture, improved water management, and sustainable land use plans should be accorded high priority to insulate the food production systems from various risks. FAO (2011) has also emphasized that healthy wetland ecosystems could play a pivotal role in reducing the risks posed by ecological (salinization) and climatic factors (drought and flood), thus sustaining the livelihoods of marginal and poor communities. Policy-driven adaptation (MGNREGA and PDS) was found to be a secondary priority for reducing the social migration, minimizing the risks of *Bhar* people becoming alienated from their original roots. Here arises the question as whether such an adaptation strategy by the marginalized peoples can really be helpful in maintaining the social-ecological resilience of threatened wetland ecosystems (Pimbert 1999). Perhaps, such communities have different needs according to their attributes (Pimbert et al. 2001). For the state, it may be important to support such marginalized groups for safeguarding their livelihoods albeit at the cost of a tangible erosion in their traditional identities and practices (Berkes et al. 2000; Singh et al. 2017).

Our results also showed despite small landholdings, *Bhar* people continue to retain ample interest in conserving wetland resources including fish, *kaul-gatta*, and *tinni*, the major traditional means of income generation. However, in the recent past, their access to wetlands has decreased considerably with the changes in institutional policies of allotting CPR on lease to the highest bidding contractors. A considerable area of *Bhar*'s traditional fishing ground is currently leased out to the individuals who rear commercial fish species like *Labeo rohita*, *Gibelion catla*, *Clarias batrachus*, etc. for higher profits, without recognizing the fact that introduction of such species has slowly wiped out many native fish species from the study area. Such changes have implications on management (Wilson 2005) and maintaining unique wetland social-ecological resilience and associated livelihoods ((Duagn 202; Bhattarai 2017). Studies have shown that marginal and indigenous groups employing location-specific knowledge (Kaschula et al. 2005) and depending heavily on social capital for their subsistence livelihoods are “conservation friendly” (Pretty 2003; Pretty and Frank 2000). The approach of *Bhar* community living around wetland is perhaps more typical, who, for example, tend to treat shallow water invertebrate fisheries, *tinni*, and other services as integral components of livelihoods resilience (*cf:* Dalzell et al. 1996). Townsend and Masters (2015) reported that local conservation practices of a particular land use system can strengthen current and future livelihood resilience if integrated with adaptation planning and strategies. In such planning, the local communities who are caretakers and users of natural resources should take part with their TEK and institutions in habitat priority-setting, restoration and management of landscape, and prioritizing the environmental services and their values for ensuring long-term social-ecological resilience.

30.6 Conclusions and Policy Implications

The study revealed that *Bhar* community is currently exposed to a set of multiple stressors including high soil pH in the upland and mid-landscapes, changes in the land tenure practices (the ease of accessing common property wetland resources has gradually reduced), and strong climatic variability impacting their livelihoods. Poor economic and educational status, weak governance and poor presence of formal institutions in the study area, small landholdings, unavailability of inputs (salt-tolerant varieties and gypsum), and social marginalization were also equally important stressors adversely affecting their livelihoods. Satellite imagery showed that in the past three decades, there had been a steady decline in the total area of wetland (*Badaila taal*) coupled with the alarming changes in upward and downward streams of wetland. This wetland has been playing a critical role in sustaining the fish diversity (up to 20 local species) and other aquatic resources (wild rice *tinni* and indigenous species of horticultural plants, for instance), as reported elsewhere also (Dugan et al 2002), and in turn serving as a firm foundation for the livelihood resilience of the *Bhar* community. If the current rates of reduction in the lake area and stream flow continue unabated and other socioeconomic and institutional stressors continue to pose risks, the sustainability of wetland-based social-ecological systems will be at grave risks.

The *Bhar* people, by harnessing the synergies of integrated land use systems and wetland resources, have not only sustained their food and livelihood needs but have also developed unique local knowledge that needs to be integrated in the co-management of wetland resources for minimizing the livelihood risks of marginal communities of the studied and other similar communities. In a nutshell, the roles of wetland resources in maintaining livelihood resilience and sustaining ecosystem services need to be considered by the policy makers. Further, environmental managers can incorporate such unique cases with system-level approach to natural resource management, where biological, social, economic, and symbolic aspects of natural resource use are nested within a broader eco-social system. Consideration should also be paid to build the capacity of local institutions and develop integration with democratic bodies to make the natural resources conservation polices effective (Gupta 1995) and to reduce the gap between *top-bottom* and *bottom-up* priorities of adapting to stressors and maintaining social-ecological resilience.

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Future Research Needs: Way Forward for Combating Salinity in Climate Change Scenario

31

R. K. Yadav, Ashim Datta, and J. C. Dagar

Abstract

Climate change, land degradation and food insecurity are serious challenges to mankind in the twenty-first century. Globally, significant cultivable area is far behind from their actual productivity potential due to soil salinity and alkalinity problems. Climate change further makes the situation more complex. To feed the burgeoning population of the country, these degraded salt-affected lands need to be reclaimed and brought under productive cultivation. Therefore, an attempt has been made to collate information on salinization processes, existing reclamation management practices and some innovative ideas such as use of flue gas desulfurization (FGD) gypsum, marine gypsum, polymers, nano-clay, nano-gypsum, municipal solid composts etc. for sodic soil reclamation. Also for saline soil management, low-cost subsurface drainage using cut soiler with crop residues as drainage material, land shaping technology, etc. have been discussed. Mention has also been made on hyperspectral remote sensing for delineation of salt-affected soil and modelling aspects for salinity/alkalinity studies for formulating proper reclamation strategies. There are many future researchable issues which have also been mentioned which would be helpful to the researchers in combating salinity under climate change scenario and help to achieve the sustainable development goals of the United Nations.

Keywords

Salinization processes · Phospho-gypsum · Marine gypsum · Cut soiler · Nano-clay · Nano-gypsum · Management practices

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31.1 Introduction

Productive natural resources, especially healthy soils and fresh water, are prerequisite to produce enough food, fodder, fibre and fuel for societal needs as well as normal functioning of the ecosystem. Salinization, among different drivers, viz. erosion, nutrient depletion and acidification, is a major driver of soil and water degradation. The problem of salt-affected soils extends over 1 billion ha area in about 100 countries (FAO and ITPS 2015). Presently ~20% of global irrigated lands suffer from salinity and/or sodicity problems to variable degree which is estimated to increase to 50% of the global arable lands by 2050. In addition to direct adverse effects on soil properties and crop yields, salt accumulation also renders freshwater aquifers saline. Adverse factors like high aridity, salinity and freshwater shortages are also severe impediments to the productive utilization of a sizeable arable area in drylands (Pannell and Ewing 2006). Nevertheless, extending the cultivation to the unused and abandoned degraded lands by adopting appropriate measures seems to be a practically feasible option to meet projected annual additional 20 million Mg of cereals and higher requirement of fruits, vegetables, fodder and feed for milk, egg and meat (UNCCD 2017). It is beyond any doubt that reclamation and management of salt-affected soils and waters are of paramount significance in improving food productivity and in easing the pressure on shrinking prime lands and fresh water. Available evidence suggests that even modest improvements in the agricultural productivity of saline and sodic lands will contribute greatly to reducing poverty and hunger in many areas of the world (FAO 2011). After thorough review of merits and demerits of different amendment-, engineering- and plant-based solutions advocated for reclaiming and managing the salt-affected soils and waters and consideration of constraints likely to be imposed by expected climatic variability, the future researchable issues have been suggested in this chapter.

31.2 Salinization Processes

Before resorting to any reclamation and management options and identifying the suitable ones, one should have clear information about the causes and processes of salinization. As such soil salinization process can be grouped into the following two types:

31.2.1 Primary Salinization

Primary salinization is the development of salts through natural processes, mainly physical or chemical weathering and transport from parent material, geological deposits or groundwater (Fig. 31.1). Soil may be rich in salts due to parent rock constituents such as carbonate minerals and/or feldspar. Closely related to this, geological events or specific formations can increase salt concentration in groundwater and therefore in overlying soil layers. This can occur when, after capillary

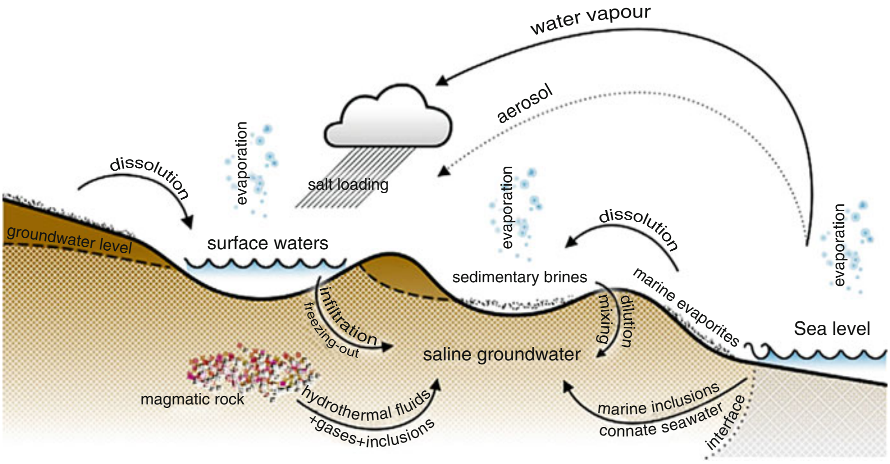

Fig. 31.1 Primary soil salinity mechanisms. (Adopted from Daliakopoulos et al. 2016)

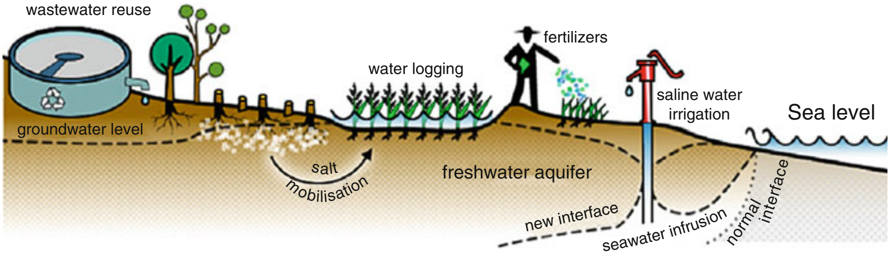

Fig. 31.2 Secondary soil salinity mechanisms. (Adapted from Daliakopoulos et al. 2016)

effects or evapotranspiration causes salinity-affected groundwater to rise, previously dissolved salts accumulate at or near the surface (Chari et al. 2012). These drivers affect the soil depending on aquifer architecture and hydraulic conductivity of geological layers and soil characteristics such as porosity, structure and texture, clay mineral composition, compaction rate, infiltration rate, water storage capacity, saturated and unsaturated hydraulic conductivity and finally potential salt content (van Beek and Tóth 2012).

31.2.1.1 Secondary Salinization

Contrary to primary salinization, secondary salinization is introduced by human interventions, mainly irrigation with saline water or other ill-suited irrigation practices often coupled with poor drainage conditions (Fig. 31.2; Fan et al. 2012; Trnka et al. 2013). With a climate predominated by little rainfall and adverse evapotranspiration rates, and soil characteristics that restrain salt leaching, arid irrigated lands are prominent salinization hotspots. While constant or increasing salt accumulation in the upper soil layers is primarily the result of irrigation sourced from highly saline water such as seawater-contaminated groundwater, moderate problems are observed even when sufficient quality water is used (Dubois et al. 2011; Mateo-Sagasta and Burke 2011). Interventions that increase time of ponding or limit sufficient drainage can also lead to salinization. An increase in water table arising due to seepage from unlined canals, reservoirs and waterlogging (Barros et al. 2012), uneven distribution of irrigation water, land clearing and improper drainage may mobilize salts that have accumulated in the soil layers (Eckelmann et al. 2006). Salty groundwater may reach the upper soil layers and, thus, supply salts to the root zone. Additional hurdles to good drainage may be posed by coastal protection infrastructure aiming to reduce seawater encroachment into the aquifers but undergo blocking natural drains rich in salt discharges. In arid regions, poorly drained soils also allow for too much evaporation leading to salt residuals on the soil surface (Mateo-Sagasta and Burke 2011; van Beek and Tóth 2012). Salinization origins can also be relevant to soil pollution. The use of fertilizers (Moreira Barradas et al. 2014) and other inputs in association with irrigation and insufficient drainage causes soil salinization, markedly in cases of intensive agriculture in compacted and limited leaching soils (Eckelmann et al. 2006). Wastewater treatment (Moral et al. 2008) and industrial (Lefebvre and Moletta 2006) or mining operation effluents are often rich in salts; therefore their mismanaged subsurface injection, surface disposal or use for irrigation can also lead to soil salinization. Finally, the use of traditional salt-based de-icing agents in excess contributes to the accumulation of salt in the soil and water (Mateo-Sagasta and Burke 2011).

31.3 Use of Hyperspectral Remote Sensing for Delineation of Salt-affected Soils

Traditional methods of identification of soil salinity based on saturation extract parameters (EC_e, pH_s, Na^+, K^+, Mg^{++}, Ca^{++}, CO_3^{2-}, HCO_3^-, Cl^- and SO_4^{2-}) require tedious processing and capital. In contrast remote sensing provides high temporal resolution and fast characterization technique of non-destructive materials. Several aerial photography and electromagnetic methods have been used by soil scientists to identify saline soils with high concentration of cations like Na^+, K^+, Mg^{2+} and Ca^{2+} and anions such as CO_3^{2-}, HCO_3^-, Cl^- and SO_4^{2-} in soil solution. But major detection difficulties of salt-affected soils with remote sensing are (1) the process goes often undetected, especially when salt minerals have not severely affected the soils, (2) the physical boundaries separating saline areas of different degree are fuzzy and (3) the process of salinization occurs not only at the soil surface but also in the soil profile, which can't be detected by optical sensors.

Moreover, in nature, salt minerals are rarely pure, since trace elements are often trapped in crystal lattices during crystallization. This affects the reflectance properties of minerals and thus hampers the use of already established experimental models. Middle infrared bands with water and OH absorption features allow distinction of soil surfaces affected by Cl^- and SO_4^{2-} salts. The imaging and non-imaging spectrometry offers considerable potential as the instruments provide high spatial resolution data in a large number of narrow contiguous spectral bands in the VNIR-SWIR region (350 to 2500 nm). As salt minerals have characteristic features occurring in the VNIR-SWIR region, they can be distinguished from one another. This information can be basically used to establish a statistical relationship between spectral properties of salt-affected soils and the various amounts of salts in soil.

Different multivariate data analysis techniques have been used for predicting various salinity-related soil properties based on significant reflectance spectral band. Among these techniques, there exists a non-significant result of partial least squares regression (PLSR) with artificial neural network (ANN) technique in respect to resulting salt concentration and measured reflectance spectra. However, this hyperspectral regression model is region specific; differentiation of various level of salinization can be properly done if the spectral properties of salt-affected soils and the principal factors are studied based on site-specific hyperspectral models. In this regard, more and more research should be directed toward the analysis of soil reflectance spectra of the major food-growing areas suffering from a different degree of salinity and sodicity. Research aimed in this direction can explore the development of spectral signatures, hyperspectral models and spectral library of SAS which will help in timely identification of different SAS parameters and in conjunction with satellite data provide real-time monitoring as well as rapid information.

31.4 Options for Mitigation of Salinization

31.4.1 Sodic Soil Reclamation

A variety of chemicals, such as gypsum, sulphuric acid or acid-forming substances like pyrite and lesser soluble limestone, etc., have been suggested for reclamation of sodic soils. But gypsum ($CaSO_4.2H_2O$), due to cost-effectiveness, easy availability and application, has proved the best amendment. General method of working out gypsum requirement (GR), to reclaim a sodic soil, neglects the role of native calcite in the exchange process. Although calcite is insoluble, factors as CO_2 enrichment in soil, irrigation water alkalinity and Ca content tend to increase its dissolution (Suarez 2001). Excess amount of sodium carbonate, often present in saline-sodic soils of the Indo-Gangetic Plains, reacts with soluble carbonates to form relatively insoluble $CaCO_3$ and the subsequent decrease in Ca of gypsum solution and ultimately overestimation of GR (Abrol et al. 1975). Excess amendment use results in inflating the reclamation costs and leaching of salts to the groundwater. Practically complete exchange reactions seldom occur under any given equilibrium between Na and Ca, thus causing Ca movements from root zone through leaching.

Therefore, development of quantitative models that have the capacity of integrating all such factors is required for precise GR determination. Similarly increasing use of underground pipes for irrigation in high RSC groundwater areas of north-western India also suggests for development of alternative technologies for amendment mixing in the irrigation water for their sustained use in irrigation (ICAR-CSSRI 2017). In addition to these constraints, continuously decreasing availability and quality of gypsum are the most formidable concerns to the use of mined gypsum as an amendment (IBM 2015). Laboratory analysis suggests that purity of currently available gypsum is ~40% (ICAR-CSSRI 2018) against the prescribed limit of >70%. Thus, there is an urgent need to evaluate and harness the alternative amendments for sodic soil reclamation.

31.4.2 Synthetic Alternatives of Mined Gypsum

The term synthetic gypsum is used to describe the industrial by-products which have potential use as sodic soil ameliorants and conditioners. Such synthetic products include flue gas desulfurization gypsum (FGDG), phosphogypsum (PG), phosphoric acid, titano-gypsum (TG), fluoro-gypsum (FG) and citro-gypsum (CG). These are by-products of coal-fired power plants and phosphoric acid-, titanium dioxide-, hydrofluoric acid- and citric acid-manufacturing industries, respectively. Recently, studies on FGDG and PG have been initiated to assess their sodic soil ameliorative effects (Zhao et al. 2018). Similarly some preliminary studies have indicated that phosphoric acid was relatively cheaper and more effective than PG in sodic soil reclamation (Gharaibeh et al. 2010), yet there is need for carrying out more conclusive studies to establish phosphoric acid as a viable amendment under field conditions. Likewise a few reports indicate the potential of titano-gypsum (Meriño-Gergichevich et al. 2010) and citro-gypsum (Kos et al. 2007) as probable amendments for acidic soils; however, their effects on alleviating sodicity stress remain unknown. Therefore, long-term systematic studies are required for developing package of suitable site-specific agro-practices to harness the potential of these synthetic alternatives of gypsum in sodic soil reclamation without accumulation of heavy metals.

31.4.3 Bio-augmented Materials

Combined use of two or more organic sources may produce better results than their single use and also reduce the dependence on relatively costly chemical amendments. One such bio-augmented formulation, comprising plant growth-promoting fungi-inoculated vermicompost, press mud and neem (*Azadirachta indica*) seed cake, was found effective in improving total organic C and soil enzyme activities in a silty loam sodic soil (pH 9.2, ESP 60) (Srivastava et al. 2016). However, studies are urgently needed on combined use of chemical amendments and such bio-augmented materials in further improvement of sodic soil reclamation efficiency of these products.

In addition to major use of “biochar” as a long-term sink for sequestering the atmospheric CO_2, recently some studies have also indicated its potential in reclamation of salt-affected soils. Improvement in sodic soil conditions with conjunctive addition of FGDG and biochar (Schultz et al. 2017; Alcívar et al. 2018) warrants for systematic studies on individual and synergic effects of biochar (B), humic substances (HS) and chemical amendments for harnessing their conjunctive use potential in sodic soil reclamation and plant growth.

31.4.4 Superabsorbent Polymers and Nanomaterials

Some studies have indicated that mixing of superabsorbent polymers (SAPs, also known as hydrogel) into soil or irrigation water either ameliorates soil or modulates plant metabolism (Shokuohifar et al. 2016; Tadayonnejad et al. 2017). Nonetheless, hydrogel application also increased Na^+ concentration in soil solution, suggesting the need to develop compounds that would not release salt ions into soil solution.

More recently, nanomaterials or engineered nanoparticles (ENPs) have also attracted attention of researchers in improvement of the infiltration rate and soil aggregate stability and decrease in the surface run-off and structural instability of sodic soils. Ghodsi et al. (2015) noticed that combined use of MSWC-coated sulphur (15 Mg ha^{-1}) and nano-iron oxide powder (20 mg kg^{-1}) decreased the pH and SAR of a saline-sodic soil. Likewise, in a highly dispersed saline-sodic soil, Luo et al. (2015) recorded that polymeric aluminium ferric sulphate (PAFS) application decreased the soil pH, EC, bulk density and $CaCO_3$ and increased the saturated hydraulic conductivity. Nano-gypsum (100%GR) was found very promising in reducing the soil pH and ESP (Kumar and Thiyageshwari 2018). Despite encouraging observations, production and use of ENPs have not gained commercial scale, so more systematic information needs to be generated for their commercialization and wider adoption by the farmers.

31.4.4.1 Nano-clay

It is an excellent option to tackle with high RSC poor-quality water which can be used for irrigation purpose. Research in this direction is needed.

31.4.4.2 Nano-gypsum

Because of high surface area, nano-gypsum can be an excellent material which can be used to reclaim alkali soils. The requirement would be lower as compared to mined gypsum, and also the purity would be higher. Further research in this direction is needed.

31.4.4.3 Marine Gypsum

Concerns on availability and quality of mined gypsum have drawn the attention on assessment and use of marine gypsum (MG) as sodic soil amendment (IBM 2015). Presence of NaCl, $MgCl_2$ and $MgSO_4$ salts in appreciable amounts in marine gypsum may increase the ionic strength of its aqueous solution by decreasing activity coefficient resulting in increased solubility of gypsum and higher reclamation efficiency than mined gypsum (ICAR-CSSRI 2017). Since combined availability of PG and MG in India is comparable to that of the total available mined gypsum (IBM 2015), there is a need for systematic studies with convincing evidence that can pave the way for their large-scale commercial use in sodic soil reclamation.

31.4.5 Other Industrial By-products

Some other major industrial by-products that have been in use for reclaiming the sodic soils include pyrite, elemental sulphur, fly ash, press mud and distillery spent wash. Despite certain beneficial effects of pyrite, slow oxidation and the presence of heavy metals have restricted its widespread adoption by farmers. In order to be as effective as soluble calcium salts, soil-applied sulphur must undergo oxidation to generate sufficient sulphuric acid for replacing the exchangeable Na^+. Recent study indicates that different combinations of reliance formulated sulphur (RFS) were comparable to 50% GR in reducing the pH of variably textured sodic soils with RFS applied 21 days before rice transplanting resulting in greater oxidation (ICAR-CSSRI 2018). Isolation and characterization of effective microbial strains of *Thiobacillus ferrooxidans* and *Acidithiobacillus*, which can hasten the rate of oxidation resulting in improved pyrite efficiency, are the need of the hour. Such strains of microbes can also help in improving the efficiency and use of elemental sulphur, a by-product of oil refineries, for sodic soil reclamation.

Press mud (PM), a by-product of sugar industry with low pH, is a rich source of plant nutrients. Sugar manufactured through sulphitation and carbonation processes results in the production of acidic sulphitation press mud (SPM) and lime rich carbonation press mud (CPM), respectively, which can be used for the reclamation of alkali soils. Studies on supplementing FGD, MG, elemental sulphur, phosphoric acid, pyrites with organic amendments including press mud, distillery spent wash and post-methanation effluent for improving their sodic soil reclamation efficiency need to be undertaken.

31.4.6 Municipal Solid Waste Compost

Recently municipal solid waste (MSW) has gained importance as an organic amendment for restoring the fertility of salt-affected soils. Composting of MSW is considered as an important recycling tool to avoid environmental and health issues associated with its land filling. It is found as a relatively low-cost and sustainable method of diverting organic waste materials including MSW from landfills while creating a quality product that is suitable for enhancing productivity of salt-affected soils. Municipal solid waste compost (MSWC) application can increase dissolution of precipitated $CaCO_3$ and soluble Ca^{2+} availability for replacing Na^+ from soil exchange complex, activity of many soil enzymes (dehydrogenase, alkaline phosphatise and urease), microbial biomass carbon and nutrient availability in a saline-sodic soil (Meena et al. 2018). However, MSWC application may sometimes inadvertently increase heavy metal concentrations, suggesting the need for systematic field experimentation and laboratory analysis to ensure the safe field application.

31.5 Saline Soil Management

Commissioning irrigation projects without adequate drainage eventually leads to rise in water table and soil salinization. The Mediterranean Basin, Indo-Gangetic Plains and the Murray-Darling Basin are facing such degradation. The judicious use of irrigation, adoption of improved irrigation practices and adequate drainage are the major factors to maintain the regional water and salt balances, but site-specific drainage interventions are also essential for rehabilitating the waterlogged salty lands.

31.5.1 Subsurface Drainage

Notwithstanding the reduction in waterlogging and salinity, and improvement crop yields, success of SSD projects often faces some socio-economic constraints. In contrast to other salinity mitigation practices suited to ‘individual’ farmer needs, SSD is essentially a community-based programme. Besides prohibitive initial costs, poor community response makes continued operation difficult in many areas underscoring the need for public-private partnerships to lower the establishment costs and campaigns to sensitize the community of long-term benefits (Ritzema et al. 2008). Safe disposal of saline drainage effluents also imposes formidable limitations in the landlocked SSD areas away from the seas. This problem can partly be overcome by developing site-specific suitable models comprising intergradations of SSD with high rate transpiring plantations (bio-drainage), evaporation ponds, conjunctive use of saline and fresh waters, cultivation of salt-tolerant crops and saline aquaculture. In addition, the regulated drainage and use of solar-powered pumps for pumping of effluents need to be assessed and standardized for site-specific situation. Twin menaces of waterlogging and salinity are essentially regional problems implying that instead of site-specific experiments, focus should be on regional modelling studies to draw valid conclusions on the nature and extent of the problem and to devise appropriate benchmarks for the cost-effective management of salt and water balances.

31.5.2 Low-cost Subsurface Drainage Using Cut Soiler with Crop Residues as Drainage Material

Recently research on this line is started in collaboration with Japan International Research Centre for Agricultural Sciences (JIRCAS). Initial land reclamation of the saline soils often requires higher drainage intensity for quick leaching of salts from the soil profile; however, drainage pipes placed at closer spacing may result in higher cost. Seeking an inexpensive degradable organic subsurface drainage material may satisfy such needs of initial drainage, low investment and a heathy soil environment. Crop straws are porous organic materials that have certain strength and endurance. In JIRCAS project, crop residues will be used to make channels at 50 cm soil depth with the help of cut soiler. The saline water will be drained out from the surface making the soil suitable for crop growth. Very little research has been conducted on this aspect. Lu et al. (2018) explored the potential of using bundled maize stalks and rice straws as subsurface drainage material in place of plastic pipes. Through an experimental study in large lysimeters that were filled with saline coastal soil and planted with maize, they examined the drainage performance of the two organic materials by comparing with the conventional plastic drainage pipes; soil moisture distribution, soil salinity change with depth and the crop information were monitored in the lysimeters during the maize growing period. The results showed that maize stalk drainage and the rice straw drainage were significantly ($p < 0.05$) more efficient in removing salt and water from the crop root zone than the plastic drainage pipes; they excelled in drainage rate, leaching fraction and lowering water table; and their efficient drainage processes lowered salt stress in the crop root zone and resulted in a slightly higher level of biomass. The experimental results suggest that crop straws may be used as a good organic substitute for the plastic drainage pipes in the initial stage land reclamation of the saline coastal soils. After decomposition, these materials improve the soil quality by sequestering carbon in soil which may be more stable at lower soil depth.

31.6 Modelling

Modelling salinity has been less explored in Indian conditions. Salinity is a dynamic and transient condition in saline soils. Chemical reactions in root zone (solubility, precipitation, cation-exchange reactions) in irrigated fields affect soil salinity and sodicity and salt leaching to drainage water. Many studies use models to evaluate salinity, sodicity and environmental hazards of drainage water as a result of irrigation (Rhoades and Suarez 1977; Shahid et al. 2013), and others calculate the effect of chemical reactions in the soil solution composition for transient conditions within the root zone. The First Expert Consultation on Advances in Assessment and Monitoring of Salinization for Managing Salt-Affected Habitats (Aquastat 2016) concluded that salinity models may face various limitations and vulnerabilities if not properly designed and developed. While state-of-the-art physical processes based models of water and solute transport can be considered, calibration and validation considering soil and crop field data as well as a solid understanding of the dynamic nature of salinity are required to produce reliable soil salinity management scenario results (Shahid et al. 2013). A major constraint to these models is usually the lack of input data (Ranatunga et al. 2008); therefore simple more robust forms are advantageous. The application of the concept of leaching requirement (LR) – the amount of water that must infiltrate the root zone to retain soil salinity within acceptable levels – can be expressed by means of easily measurable and robust properties, such as the water content of soil at field capacity and in the saturated paste. The LR component has motivated research on drainage improvements as a direct way to simulate the necessity of drainage.

Based on this concept, various transient LR models (e.g. WATSUIT, TETrans) (Corwin et al. 2007) have been developed as well as more advanced software that while focussing on salinity/sodicity problem also includes other complex key process (e.g. UNSATCHEM) (Shahid et al. 2013). This advanced code has been used successfully to understand both salinity and sodicity process dynamics at a very local scale. Other software, such as LEACHM, PHREEQC, HYDRUS and ORCHESTRA, are less focussed to soil salinity issues (van Beek and Tóth 2012). Apart from these models, a range of mostly black box data-driven models have been applied for case-specific studies (Zou et al. 2010). The systematic review of models reveals that Mediterranean countries attract scientific attention for secondary salinity applications, with the SALTMED LR model (Ragab 2002) being the most popular in field applications. Therefore, salinity study using models can be given more emphasis in the context of climate change.

31.7 Saline Effluent Reuse

Recycling saline effluent in irrigation is a useful option in areas which also have freshwater availability at the time of pre-sowing irrigation. Saline drainage water when reused in cyclic or blending mode can also partly contribute to the lowering of shallow water tables. Long-term experiments have shown that saline effluents can be profitably recycled for producing wheat, pearl millet, sorghum, sunflower, barley, rye grass, Egyptian clover, Persian clover etc. with only slight to moderate reductions in economic yields (Sharma et al. 2005; Yadav et al. 2003, 2007), especially if canal water is available for blending and for providing a few irrigations at critical stages. Cultivation of crops capable of enduring excess salts may further increase the acceptability of this practice. Commercial cultivation of high value seaweeds can be a profitable venture in poorly drained coastal saline lands (Subba Rao and Mantri 2006). Land shaping models have paved the way for commercial fish culture in waterlogged salt-affected lands of central Indo-Gangetic Plains and some saline coastal areas of India. However, for making more productive reuse of saline effluents, stage-dependent osmotic and matric stress tolerance limits of suitable site-specific crops with optimal irrigation schedules need to be worked out.

31.8 Land Shaping Models

Vast area of sodic soils suffering from waterlogging, with shallow water table (≤ 2 m) and no response amendments, suggests the need for standardizing alternative land shaping approaches to improve their productivity (Verma et al. 2015). For amelioration of such waterlogged sodic soils, land shaping techniques should be devised for making provision of fish pond and raised land to grow vegetables for higher returns. Similarly land shaping techniques need to be standardized for flat coastal salt-affected soils with poor water sorptivity and natural drainage and receiving intense rainfall. Under such conditions, backwater flows may further reduce the efficiency of surface drainage for removing the excess water. Here simple earth replacement techniques like farm pond and integrated rice-fish cultivation can be promising solutions for land use intensification. Rainwater harvested in these structures not only reduces the soil salinity but also ensures ample availability of fresh water for irrigating the winter season crops (Mandal et al. 2017).

31.9 Plant-based Solutions

The plant-based approach is an adaptive way of improving the productivity of salt-affected soils by growing the salt-tolerant crops and cultivars. Of late, molecular techniques have become an integral part of varietal improvement and screening trials. Identification of genes and molecular traits underpinning salt tolerance can ultimately pave the way for their incorporation into popular salt-sensitive cultivars through conventional and marker-assisted breeding approaches. Integrated use of amendments and salt-tolerant cultivars can save up to three fourths of reclamation costs in sodic areas and produce acceptable yields in waterlogged saline lands. There is evidence that in addition to producing stable yields, several tree, shrub and grass species in agroforestry and agri-horticulture systems may bring out tangible improvements in soil quality over time.

31.9.1 Disposal of Sewage Effluents in Tree Plantations

Properly treated effluents can be used in pisciculture and irrigation of perennial tree crops used for fuel and timber (Kamyotra and Bhardwaj 2011). Certain agroforestry plantations are considered a safe sink for disposing the wastewater. Fast-growing, short rotation tree species such as *Eucalypts*, *Populus* and *Salix* besides remediating the wastewater-contaminated soils can also provide socio-environmental benefits in terms of fuel, timber and carbon sequestration (Rockwood et al. 2004). Nonetheless, similar to other crops, different design and management factors like rotation period, water and nutrient needs and tolerance to salinity and heavy metals greatly influence the ability of trees in wastewater removal. For the best results, location- and tree-specific irrigation methods and water quality guidelines need to be developed. Environmentally safe irrigation methods are needed to ensure that nutrient additions through wastewater match the plant needs so that excess nutrients do not leach to the groundwater posing pollution risks.

31.10 Improved Irrigation Methods

Climate change impacts (high temperature, erratic rainfall and reduced river flows) are dealing a severe blow to freshwater supplies in many areas of the world. These inevitable changes in land and water use dynamics imply that agricultural production will have to increasingly depend on poor soils and waters. Currently, farmers in several areas have no other option but to utilize low-quality water in irrigation and soil reclamation. Under such conditions, a well-thought-out strategy including integration of low water-requiring crops in the existing cropping systems, adoption of salt-tolerant cultivars, use of amendments and water use of efficient micro-irrigation techniques has become absolutely essential. Method of irrigation is one the major factors that govern crop water use efficiency and salt accumulation in soil. Pressurized methods of irrigation, i.e. sprinkler and drip, are increasingly used for the uniform application of water while curtailing the water wastages and ensuring adequate leaching, especially in areas having poor drainage. Development of suitable irrigation water quality guidelines for micro-irrigation methods for different agro-edaphic conditions is very essential for achieving sustainable higher water use efficiency.

31.11 Managing Seawater Intrusion in Coastal Areas

Although both natural and human processes affect the rate of salt ingress, climate change-induced sea level rise has recently emerged as a major driver of seawater ingress. According to the Intergovernmental Panel on Climate Change (IPCC) projections, sea level can rise by at least 110 mm and even up to 880 mm in worst case scenario by the end of the twenty-first century, accelerating the inland migration of the mixing zone between fresh and saline water (cited in Werner and Simmons 2009). High sensitivity of coastal aquifers to SWI is ascribed to “upconing” – the process by which saline water underlying fresh water moves upward due to continued pumping. In extreme cases, pumping may have to be stopped to prevent further deterioration in water quality. Upconing occurs because fresh water floats over the denser saline water as a thin layer; with a unit drop in fresh water, saline water may rise by up to 40 units. It is due to this reason that careful skimming of freshwater layer instead of pumping is recommended for the productive management of coastal aquifers (Dhiman and Thambi 2010).

Several solutions have been suggested for preventing the mixing of salty seawater into coastal aquifers by maintaining the groundwater levels. Construction of large recharge pits and surface spreading of water can partly replenish the groundwater. Nonetheless, these interventions may be cost prohibitive and inefficient in excessively pumped unconfined aquifer systems (Narayan et al. 2007). Injection wells or subsurface barriers can also be suitable interventions for preventing SWI and improving water quality in some coastal areas (Allow 2012). The location and penetration depth of recharge wells and subsurface flow barriers are the major factors controlling SWI in unconfined coastal aquifers. For example, injection of recharge water at the toe of saltwater wedge proves very effective in deterring SWI. Similarly, more effective saltwater repulsion can be achieved when barriers are placed deeper and closer to the coast (Luyun Jr et al. 2011). Despite proven benefits, ample precaution is necessary while employing such measures. One study conducted in a coastal area of the Mekong River Delta, Vietnam, where sluices for controlling SWI were constructed and operated in a phased manner revealed positive impacts in upstream areas but adverse effects in downstream parts. While canal water salinity declined rapidly upstream (western part) of sluices leading to increased rice production, reduced supply of brackish water adversely affected brackish water shrimp farming in the eastern part, reflecting the high sensitivity of coastal lands to the external interventions (Tuong et al. 2003).

31.12 Conclusions and Future Perspective

Sustainable development goals (SDGs) emphasize for sustainable use of land and water resources as the top priority for combating land degradation and desertification. Excess salts in soil and water have resulted in physical and chemical degradation of millions of hectares of potentially arable lands across the world. However, the problem has attained alarming proportions in the past few decades in many irrigated basins like the Mediterranean Basin, the Indo-Gangetic Plains and Murray-Darling Basin. Though several efficient solutions have been developed for reclaiming and managing the salt-affected soils and poor-quality waters, but to manage dynamic nature of salinity problem, continuous evolvement of new site-specific low-cost practically feasible strategies is warranted.

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