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Editors

Sustainable Management of Soil and Environment

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About the Editors

Ram Swaroop Meena was born into a farming family and obtained his master's and doctorate degrees in agronomy from Swami Keshwanand Rajasthan Agricultural University, Bikaner, Rajasthan. Dr. Meena was awarded a Raman Fellowship from the Ministry of Human Resource Development (MHRD), Government of India (GOI). He completed his postdoctoral research on soil carbon sequestration under Prof. Rattan Lal from Ohio State University, USA. Dr. Meena has 9 years' research and teaching experience at UG/PG/Ph.D. levels and is currently running three externally funded projects on soil sustainability, crop productivity, and efficient use of resources. He has published more than 100 research and review papers in leading peer-reviewed journals, contributed 25 book chapters, and has published 4 in Indian books and 6 international books. He has also been involved in developing 2 textbooks for schools. He has received numerous awards, including Young Scientist, Young Faculty, Global Research, Excellence in Research, and Honorable Faculty Award. Dr. Meena is a member of 9 respected national and international societies, a member of the editorial boards of 12 peer-reviewed journals, and has attended numerous national and international conferences. In addition, he coordinates training courses, meetings, workshops, and farmers' fairs.

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Jitendra Singh Bohra is a Professor and Head of the Department of Agronomy, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, India, where he also completed his M.Sc. (Ag.) agronomy and Ph.D. degree. He was a Postdoctoral Researcher at the University of Hamburg, Germany. He has received CSIR junior, senior, and postdoctoral fellowships and possesses over 33 years of teaching and research experience in the area of nutrient management and farming systems. He is in-charge of the ICAR Varanasi Centre of Integrated Farming Systems and has more-than 90 publications including books, book chapters, manuals, bulletins, reports, and research papers. As CCPI, he has been involved in mega projects, such as the World Bank-funded Component 3 of the "National Agricultural Innovation Project" and an NMSA-funded project for the Ministry and Agriculture and Farmers' Welfare. He has participated in several national and international conferences and traveled to Asia, Europe, and the USA for academic purposes.

Mangi Lal Jat is a Principal Scientist/Systems Agronomist and Sustainable Intensification Strategy Lead at the International Maize and Wheat Improvement Center (CIMMYT). After obtaining Ph.D. degree in agronomy from ICAR-Indian Agricultural Research Institute (IARI), New Delhi, he served at the Indian Council of Agricultural Research (ICAR) as a Systems Agronomist for 11 years. He devoted two decades to intensively working on basic and applied science in agronomy, soils, and environment and promoted conservation agriculture (CA)-based sustainable intensification in smallholder systems of Asia. His research on CA has provided scientifically sound basis and directions for promoting sustainable intensification through policy changes and led to impact at scale in smallholder systems of south Asia. He has been on forefront in capacity building to develop new cadre of researchers across the Asian countries. Research results of his group have been well documented in over 300 peer reviewed high-impact journal articles, book chapters, books, manuals, monographs, and proceedings. He has served several reputed international and national scientific bodies and fora including Food Agriculture Organisation (FAO) and International Society of Precision Agriculture in various capacities. A Fellow of the National Academy of Agricultural Sciences (NAAS) and Indian Society of Agronomy, Dr. Jat has several awards and recognitions to his credit including ICAR's prestigious Rafi Ahmed Kidwai Award 2018.

Soil and Environmental Management

1

Sathiya Bama Kaliappan, Yazhini Gunasekaran, R. Smyrna,
and Ram Swaroop Meena

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Abstract

Climate change is a variation in atmospheric properties due to natural and human activities over a long period of time. In the last few decades, there was a significant change in the gaseous composition of earth's atmosphere, mainly through increased energy use in industry and agriculture sectors, viz. deforestation, intensive cultivation, land use change, management practices, etc. These activities lead to increase the emission of carbon dioxide (CO_2), methane (CH_4), nitrous

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oxide (N_2O), etc., popularly known as the "greenhouse gases" (GHGs), and rise up the temperature. These GHGs cause regional and global changes in the climate-related parameters such as rainfall, soil moisture, and sea level. Intergovernmental Panel on Climate Change (IPCC) projected temperature rise from 0.5 to 1.2 ° C by 2020, 0.88 to 3.16 °C by 2050, and 1.56–5.44 °C by 2080 for India. To mitigate this climate change, among the different means, soil is also one of the key components of the agricultural production system, and it needs to be relooked in the view of the environment. Soil not only acts as a sink for GHGs but also as a source from agriculture. In this regard, concerted efforts are necessary for adverse climate change impact to reduce the vulnerability of agriculture. To meet out these issues, sources and mitigation options for individual gases from the soil are discussed in this chapter. Sources of CH_4 emission are due to microbial decomposition of soil organic matter (SOM) under the submerged condition, burning of crop residue, and the enteric fermentation. The N_2O is through fertilizers by the process of nitrification and denitrification. The major carbon (C) sources are tillage, burning of crop residue, and fossil fuel combustion. To overcome the emission of GHGs from the soil, the nature of the release of individual gas and its specific management can give an idea of sustaining soil health to safeguard the environment. Hence, reducing these GHGs emission from the soil through light to overcome the climate change effect. Reduction of CH_4 gas mainly from rice can be done by the adoption of intermittent irrigation, planting methods, fertilizer type, etc. Nitrification inhibitors from plant-derived organics such as neem oil, neem cake, and Karanja seed extract could also reduce the N_2O emission. Also, the demand-driven nitrogen (N) application using a leaf colour chart (LCC) reduces N_2O emission. By using legume crops in rotation helps to reduce the N_2O emission besides fixing long time C in the belowground. To reduce CO_2 emission from the agriculture, sequestering C through agroforestry system, conservation agriculture, perennial crops, etc. could be the effective strategies for assimilating and storing C for a long time in soil.

Keywords

Methane · Carbon dioxide · Nitrous oxide · Sources · Soil · Mitigation · Environment

Abbreviation

AMF	Arbuscular mycorrhizae fungi
C	C
CH_4	Methane
CO_2	C dioxide
FAO	Food and Agriculture Organization
Fig	Figure
FYM	Farmyard manure

GDP	Gross domestic production
Gg	Gigagram
GHG	Greenhouse gas
Gt	Gigatonne
GWP	Global warming potential
INM	Integrated Nutrient Management
IPCC	Intergovernmental Panel on Climate Change
LCC	Leaf colour chart
Mg	Megagram
MT	Metric tonnes
NICRA	National Initiative in Climate Resilient Agriculture
PM	Poultry manure
SIC	Soil inorganic matter
SOC	Soil organic matter
T	Tonne
Tg	Teragram
UNFCCC	United Nations Framework Convention on Climate Change
USEPA	United States Environmental Protection Agency
Yr	Year

1.1 Introduction

Agriculture is crucial to get ensured food, nutrition, and livelihood security of developing country like India. Two thirds of India's population depend on agriculture and account for a significant share in country's gross domestic product (GDP). Agriculture is the primary source for supplying raw materials for industry. Its linkage with other economic sectors has a multiplier effect on the entire economy of the country. The agricultural activities, viz. clearing of lands, crop cultivation, irrigation, livestock unit, fisheries, and other activities, have an impact on the GHG emission and lead to climate variability (Solomon et al. 2007; Yadav et al. 2017). Over the 250 years, CO_2 is the most important human-induced GHGs followed by CH_4 and N_2O. Based on the United Nations Framework Convention on Climate Change (UNFCCC) policy, India has planned to reduce 20% of GHG emission intensity by the year 2020. Current variations in rising sea level and glacier melting cause global climatic change. It increases the concentration of atmospheric GHG. These released from the earth surface cause the greenhouse effect, i.e. trapping of energy by the GHG in the atmosphere and leading to a rise in temperature. If it does not exist, cooling of the earth might have taken place, and ice would cover earth from pole to pole. For normal growth, development, and existence, the greenhouse effect is important. Past 4.65 million years of earth history, many times earth has warmed up naturally. But currently, due to human activity, rapid warming happened. Earth's average temperature is about 150o C (590 F), and it has risen during the last century by about 10 F. The rise would be 2.5–10.40 F by the year 2100. According to IPCC

(2007) fifth assessment report, warming of the atmosphere is not uniform and it is unequal. The main causes for increasing this global warming are by anthropogenic influences only. Gupta et al. (2002) also reported the same for developing country like Indian scenario. The climatic variation causes changes in the agricultural activity. Season variation expected during 2070 in a country like India is about 0.2–0.4 °C in Kharif and 1.1–4.5 °C during Rabi season (Pathak 2015).

The effect of GHGs measured as global warming potential (GWP) is a measure of the contribution of a given mass of greenhouse gas to global warming. GWP is calculated for a specific period of time and depends on the absorption of infrared radiation by a given species, spectral location of absorbing wavelengths, and species lifetime in the atmosphere. Thus, GWP for CO_2 is taken as 1, for CH_4 it is 25, and for N_2O it is 298. The GWP is calculated based on the 100-year time horizon. For example, GWP of one unit of CH_4 and one unit of N_2O is equal to 25 times and 298 times that of CO_2, respectively.

$$\mathrm{GWP} = \mathrm{CO_2} + \mathrm{CH_4} \times 25 + \mathrm{N_2O} \times 298$$

The current levels of CO_2, CH_4, and N_2O concentration are 401 ppm, 1789 ppb, and 321 ppb, and it increased from pre-industrial era (AD 1000–1750) to current time up to 73%, 45%, and 18%, respectively (Solomon et al. 2007; Meena and Meena 2017). In a developing country like India, a high level of fertilizer usage, other agricultural inputs, and increasing livestock population are the major sources of GHG emissions from agriculture. However, the contribution of Indian agriculture to total GHG emission has been decreased from 33% in 1970 to 15% in 2014. But, the unavoidable faster growth rate of industry, transport and energy sector has the possibility to reduce GHGs. Presently India contributes 5% of world GHG emission of 50 billion tonnes of CO_2 equivalent. Indian energy sector contributes 65% followed by 18% by agriculture and 16% by industry. Within agriculture, enteric fermentation share is 56%, followed by 23% from soil and 18% from rice fields and remaining 1% from on-farm burning of crop residues and 1% from manure management (Pathak 2015). The impact of climate change indicated an alarming bell on fertilizer use and its efficiency, organic C retention, soil erosion, etc., which causes severe droughts and floods and will decline the arable areas (Gupta et al. 2002; Yadav et al. 2018). It has its adverse effect on soil properties too, viz. reduction in quality and quantity of organic C, slow rate of decomposition by high C:N ratio, increased gaseous losses of N due to high soil temperature, etc. (Pathak 2015; Ram and Meena 2014).

Thus, global warming is an important issue. The ways and means of mitigating the GHGs responsible for global warming are essential. Among the different strategies, agricultural practices also one to mitigate climate change through sequestering C in soil and reducing the emission of CH_4 and N_2O from the soil through land use changes and other management practices. The cultural practices such as residue mulching and reduced tillage or zero tillage encourage the soil C build-up. The proper management of fertilizers, manures, and irrigation can reduce the emissions of N_2O and CH_4. These options could reduce global warming besides improving soil fertility. In addition to that, the substitution of fossil fuel by biofuels for energy production also possibly reduced the GHG emission. The other options like changing cropping pattern by including legumes, perennials, or deep root systems could increase the C storage in soil.

Policies and incentives are essential to encourage the farmers to adopt these mitigation strategies besides the benefits of improved soil fertility. Managed soils are the prime source of N_2O and CH_4. Jain et al. (2014) reported that GWP has been ranged from 3500 to 3700 kg CO_2 eq/ha in continuously flooded rice and the rice grown with intermittent flooding released 900–1050 kg CO_2 eq/ha, whereas the other crops like wheat, maize, millets, oilseeds, pulses, and vegetables contribute to 340–450, 320–365, 230–250, 220–275, 180–240, and 440–575 kg CO_2 eq/ha, respectively. Through agriculture, the emission of GHGs could be mitigated cost-effectively by adopting low C technologies and management practices. For example, the practices of improving the efficiency of N often reduce N_2O emission. In agriculture, any practice that slows down the release of C from the soil could also act as a sink of C.

Soil contributes a major share of 37% GHG emissions, and it could be reduced by sequestering some CO_2 in soil and in turn improve soil fertility and productivity by improved management practices. According to IPCC (2013) report, 1500 billion tonnes of C is stored in the soil which is double the amount of C in the atmosphere. 1.2 billion tonnes of soil C storage is possible in agriculture (IPCC 2014). Lal (2006) added that 24–40 million tonnes of more production of grain is possible every year in Africa, Asia, and South America by storing SOC pool of 1 tonne per year per hectare of land.

By considering the above points in mind, sustainable management of soil and environment topic is discussed in this paper by collecting the literature from the published papers and the experiences. This chapter present a way that, the sources of GHGs, mitigation of GHGs, and new concept of mitigating climate change to managing the soil and environment.

1.2 Sources of Methane Emission from Agricultural Soil

Mostly CH_4 is emitted from agriculture by rice cultivation next to ruminant emission. CH_4 is produced under anaerobic condition during microbial decomposition of SOM accompanied by favourable conditions, viz. continues submergence, high level of C content, and fresh organic manure use in puddled soil. Crop residue burning especially in situ conditions also contributes to CH_4 budget. Over 100 years, GWP of methane is about 25 times powerful than CO_2 (Forster et al. 2007; Meena et al. 2018). Globally CH_4 contributes about 16% of the GWP, and its contribution triples since the pre-industrial times and now at present seems to be static or decreasing. CH_4 emission from the cultivation of rice differed widely and reported range (Chen et al. 2015; Sofi et al. 2018; Meena et al. 2015d) is 39 and 112 Tg CH_4/year. In the Asian region, CH_4 emission accounts for 25.1 Tg/year, of which India emitted 5.88 Tg and China emitted 7.67 Tg. Yan et al. (2003) reported a CH_4 emission of 28.2 Tg/year from rice fields.

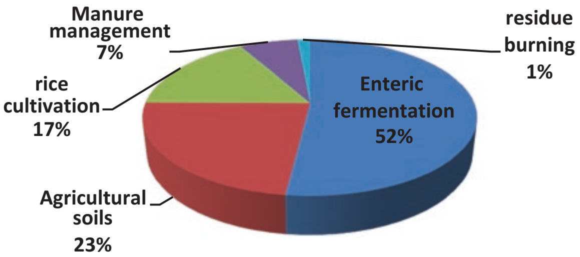


Fig. 1.1 Relative contribution of agricultural components to CH_4 emission (Bhatia et al. 2013)

Based on several estimates of CH_4 emission from rice soils, it has been rationalized from the previous estimation of 37.5Mt to 3.5Mt (Bhatia et al. 2013; Yadav et al. 2018a). They also added that similar trend of CH_4 emission data reported by the global atmospheric research, FAO and United States Environmental Protection Agency (USEPA), and UNFCCC during 2010. The relative contribution of agricultural components to CH_4 emission indicated that enteric fermentation contributes 211 MT of CO_2 equivalent of GWP followed by agricultural soil (94 MT of CO_2 equivalent), rice cultivation (68 MT of CO_2 equivalent), manure management (MT of CO_2 equivalent), and crop residue burning (6 MT of CO_2 equivalent) (Fig.1.1).

In rice fields CH_4 presents as a gaseous form or dissolved one (Tokida et al. 2005; Meena et al. 2016). According to Strack and Waddington (2008), 33–38% of CH_4 is in the gaseous phase. Green (2013) reported that the amount of dissolved CH_4 is low due to its low solubility (17 mg/lit) at 350C in water and lack of ionic form. The organisms, viz. methanogens, methanotrophs, and atmospheric soil CH_4 link, are responsible for the regulation of the total soil CH_4 cycle. There are three possible mechanisms by which CH_4 is emitted to the atmosphere, viz. diffusion, ebullition, and plant-mediated transport. The diffusion is a slow process of CH_4 emission, physical in nature, and less in amount of flux from the soil due to less soluble in nature. The diffusion process is very low in clay soil and high in sandy soils due to pores. According to Neue (1993), deep water rice diffusion is active in the upper column of water. Diffusion also limits the plant-mediated CH_4 transport by enriching the plant rhizosphere at a threshold level of CH_4 concentration.

Another process of CH_4 emission from rice soil is ebullition in which CH_4 transported in the form of bubbles (Rosenberry et al. 2006; Meena et al. 2015; Yadav et al. 2017a). It is a common mechanism and thought to be a faster process than diffusion. High organic matter content favours this process. Schutz et al. (1989) reported that ebullition process contributes 4–100% (depend on season) of CH_4 emission from a rice field in Italy. Butterbach-bahl et al. (1997) reported that 10% of CH_4 is emitted through ebullition process during the first few weeks. According to Tokida et al. (2013), a significant total amount of CH_4 is emitted from rice field, i.e. 26–45% at panicle initiation and 60–68% at heading stage through (based on bubble volume) ebullition only. Another important process of CH_4 emission is through biological means, i.e. by aerenchymatous tissue. Aerenchyma's main function in the plant is the transportation of oxygen for root respiration in rice. Aerenchyma is a modified parenchymatous tissue with air vacuoles to make up the

Table 1.1 Seasonal CH_4 emission from rice fields at different locations in India

Location	Methane (kg ha^{-1})	No. of observations	Average (kg ha^{-1})
Nadia, West Bengal	108–290	3	158
Purulia, West Bengal	110	1	110
Barrackpore, West Bengal	18–630	3	222
Jorhat, Assam	97–460	5	175
Tezpur, Assam	10–14	2	11.7
North 24 Parganas West Bengal	145–462	2	305
Cuttack, Orissa	7–303	44	91
Bhubaneshwar, Orissa	140–186	2	163
New Delhi	10–221	68	39
Allahabad, Uttar Pradesh	5	1	5
Kumarganj, Uttar Pradesh	20	1	20
Maruteru, Andhra Pradesh	150	1	150
Madras, Tamil Nadu	110–182	2	149
Trichur, Kerala	37	1	37
Trivandrum, Kerala	90	1	90
Kasindra, Gujarat	120	1	120
Pant Nagar, Uttarakhand	54–114	4	79
Kamal, Haryana	64–100	2	81
Varanasi, Uttar Pradesh	0.1–261	15	117
Raipur, Madhya Pradesh	4–109	6	34
Ludhiana, Punjab	452–1650	5	875

Pathak (2015)

plant to adopt flooded condition (Armstrong 1978). According to Setyanto et al. (2016), plant-mediated transport contributes 80–90% of the CH_4 flux from the rice field. Nouchi et al. (1990) reported that primarily CH_4 is released through the micropores in the leaf sheath of lower leaf and released through stomata in the leaf hole. Pathak (2015) reported the seasonal CH_4 emission from rice fields at different locations of India (Table 1.1).

1.3 Sources of Nitrous Oxide Emission from Agricultural Soil

N_2O is a gaseous intermediate in the reaction sequence of denitrification and by-product of nitrification in the soil. The availability of inorganic N is the main factor for these reactions which is applied through external application of N by synthetic or organic fertilizers (Fig. 1.2). Emission of N_2O from Indian soils was 259 Gg and 45 Gg, respectively, from direct and indirect means. The largest source for N_2O emission is fertilizer which contributes 77% to direct N_2O emission (Pathak 2015).

Six percent of the anthropogenic greenhouse gas emission is contributed by N_2O and increasing by about 0.25% per year. During the pre-industrial era, N_2O concentrations recorded was 270 ppb, and it increased up to 319 ppb in 2005. According to

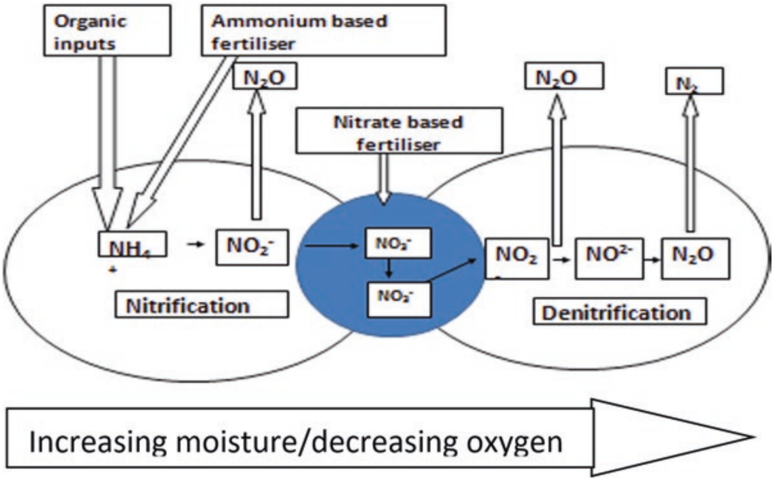


Fig. 1.2 *Pathways* of N_2O emission

IPCC (1996) and Denman et al. (2007), N_2O emission range from 14.7 to 17.7 Tg N_2O/year. Mostly more than 50% of the N_2O emissions are from agriculture and biomass burning. Fertilized arable land contributes at 3.3 Tg N_2O/year and 1.4 Tg NO-N/year globally (Stehfest and Bouwman 2006). Based on IPCC report, fertilizer-induced N_2O emissions (at the rate of 1.25 + 1% of the N) ranged between 0.77% for rice and 2.76% for maize.

1.4 Sources of Carbon Dioxide Emission from Agricultural Soil

In agriculture, soil management practices such as tillage, land use, fertilizer, manure application, crop burning, etc. contribute to CO_2 production. These practices trigger the decomposition of soil organic matter and release CO_2 gas. Tillage breaks up soil aggregates and exposes the surface area of organic material, promoting their decomposition. Fuel usage in different agricultural operations and crop residue burning are other sources of C emission. Off-farm production of CO_2 during the manufacturing of fertilizers, pesticides, and farm implements is also a source for global warming. The data pertaining to C produced by various agricultural practices are given in Table 1.2.

CO_2 globally cycles among atmosphere, ocean, and lithosphere. The atmosphere contains C as CO_2 of 785 Gt which is equal to approximately 15 t C above each hectare of the earth. The total amount of CO_2 exchanged between the land surface and the atmosphere is approximately 120 Gt C/year. From this, half of it is released through respiration by plants (Denman et al. 2007; Meena et al. 2017).

Atmospheric CO_2 concentration globally increased by 110 ppm to 385 ppm in 2008 from 275 ppm during the pre-industrial era. According to Denman et al.

Table 1.2 C produced by various agricultural inputs and practices

Inputs	Pretty et al. (2003)	Lal (2004)
Fertilizers	kg C/kg	kg C/kg
N	0.98–1.57	0.9–1.8
Phosphorus	0.11–0.17	0.1–0.3
Potassium	0.10–0.15	0.1–0.2
Lime		0.03–0.23
Pesticides	kg C/kg	kg C/kg
Herbicides	3.57–5.71	6.3
Fungicides	1.38–2.21	3.9
Insecticides	2.99–4.48	5.1
Agricultural operations		(Lal 2004)
One spray		1–1.4
Tillage operations		2–20
Drilling or seeding		2–4
Combine harvesting		6–12
Conventional tillage		35.3
Minimum tillage		7.9
No-tillage for seed bed preparation		5.8
Pumped irrigation using sprinkler		129

(2007), atmospheric CO_2 load increased at the rate of 4.1 Gt C/year during 2004–2005. During the 1900s, land use changes and management estimated to contribute 6–39% of the CO_2 growth rate. While converting natural ecosystem, the agriculture causes depletion of SOC pool by 60% in temperate regions and 75% in cultivated soils in tropics. Benbi et al. (2012) reported that land use and management practice has a greater role in CO_2 emission than fossil fuel burning until the beginning of the twentieth century.

Based on IPCC values, globally SOC pool consists of 2500 gigatonnes (Gt) which include 1550 Gt of SOC and 950 Gt of soil inorganic C (SIC). SOC pool is 3.3 times greater than the atmospheric pool (760 Gt) and 4.5 times that of the biotic pool (560 Gt). The SOC stock of 1 m depth ranges from higher side 800 t/ha in organic soils to 30 t/ha in an arid climate with an average value of 50–150 t/ha.

1.5 Mitigation of Methane Emission

Among the different agricultural ecosystems, wetland ecosystem is the prime source for methane emission. A large amount of CH_4 emission in rice fields generated through methanogenesis under anaerobic conditions and low oxidation-reduction potentials (Mer and Roger 2001; Meena et al. 2017a). In that case, reducing methanogenesis in rice soils or improving CH_4 oxidation in well-aerated soil will be the best management strategy for mitigating CH_4. Its emission also depends on organic matter incorporation (crop residues). Increases in CH_4 production were reported under rice farming when straw was added from 0 up to 7 t/ha (CH_4 emission from

100 to 500 kg/ha/year) (Sanchis et al. 2008; Mitran et al. 2018; Yadav et al. 2017b). For managing rice straw in the field, recommended practices are composting of rice straw, straw burning under controlled condition, and biochar production using rice straw as a substrate for other products production. The other agronomic practices which could reduce the CH_4 emission are midseason drainage and intermittent water supply which prevent the development of soil reductive condition. GHG emission reduced to 50–90% compared to continuous flooding by draining one or two times during rice growth period (Pathak et al. 2015). Gupta et al. (2002) conducted a study in Indian condition and reported that CH_4 flux reduced to 6.9 g/m2 from 15.3 g/m2 for continuous flooding. CH_4 emission also depends on the source of fertilizer used. Hence, water management and fertilizer use are important components controlling the CH_4 flux. The intermittent flooding or alternate wetting and drying has been reported by many scientists to decrease CH_4 emission. Pathak et al. (2013) reported that by changing the water management from present practice to the above practice in all the rice growing areas of Indian country could reduce the national CH_4 flux by 40% from 0.79 Tg to 0.49 Tg. They also added that intermitted flooding increased the N_2O fluxes to 14.27 Gg from 13.46 Gg N/year. Since the N_2O possesses higher GWP, the increased N_2O might be reducing the benefit of the decreasing CH_4 and CO_2 fluxes. Anyway, GWP of irrigated rice ecosystem of India has reduced by 13% from 154 Tg to 134 Tg CO_2 equivalent/year. Direct seeding of rice and system of rice intensification could be the potential options for CH_4 emission reduction.

Type, rate, and fertilizer application methods to rice influence the CH_4 emission. Dong et al. (2011) reported that 50% of CH_4 emission reduction is possible by proper N management in rice. Ammonium-based N fertilizers have the potential to reduce CH_4 emission than urea (Linquist et al. 2012; Meena et al. 2018a). Ali et al. (2012) reported that application of ammonium sulphate to the rice field reduced the CH_4 emission by 23%. But 25–36% was reported by Corton et al. (2000). Application of silicate fertilizer at the rate of 10 t/ha could mitigate CH_4 emission by 28% (Ali et al. 2008; Varma et al. 2017). Decreased CH_4 emission is also noticed by the researchers with ammonium nitrate application. Application of K could reduce CH_4 emission by reducing soil redox potential and stimulating CH_4 oxidation (Hussain et al. 2015; Meena et al. 2014). Ali et al. (2008) reported that application of 30 kg K/ha reduced CH_4 emission by 49% as compared to no K application. The organics like biochar reduced the CH_4 emission in rice compared to farmyard manure application (Pandey et al. 2014). Depnath et al. (1996) observed that biogas slurry as manure resulted in reducing CH_4 emission than FYM. Azolla and cyanobacteria facilitate the CH_4 reduction by increasing dissolved oxygen and reducing redox potential and promoting CH_4 oxidation at the soil-water interface (Hanson and Hanson 1996). Application of ammonium sulphate reduced the CH_4 emission by 30–60% compared with urea by maintaining favourable redox potential (Mosier et al. 1998). The picture given below (Fig. 1.3) lists the various practices which are reducing/producing the CH_4 emission in rice fields.

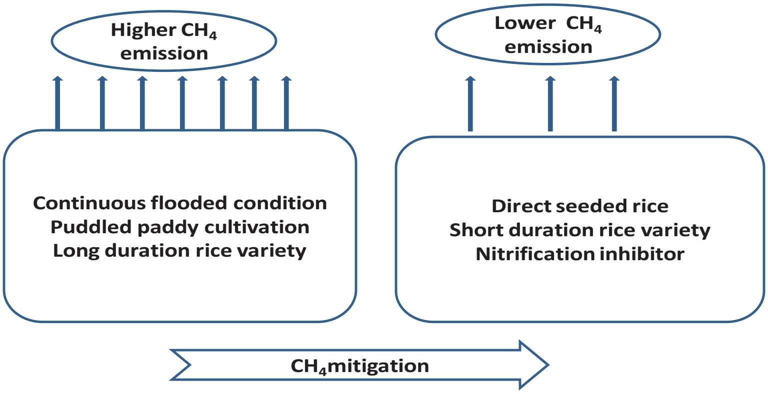


Fig. 1.3 Ways of CH_4 emission from rice fields

1.6 Mitigation of Nitrous Oxide

Use of Nous fertilizer alone contributes to more than 70% of the N_2O emission. Reducing N usage could reduce the N_2O emission. One of the processes to mitigate N_2O emission is by improving the efficiency of N use. The synchronized N supply with crop demand, use of nitrification inhibitors, and fertigation through drip or sprinkler irrigation can reduce N_2O emissions. According to Pathak et al. (2015), among the nitrification inhibitors, Nimin has higher mitigation potential (25–35%), and the neem cake has lower mitigation potential of 10–21%. More N_2O is emitted from the arable soils than any other human-induced sources. Jain et al. (2014) reported that reducing this N_2O emission and GWP by about 11–14% is possible for mitigation opportunity (Bhatia et al. 2012; Varma et al. 2017a; Jain et al. 2014). On average, about 1% of the applied N is directly emitted as N_2O. Miller et al. (2010) reported that corn farmers could reduce N_2O loss by 50% by adopting conservative fertilizer practices. They also proposed conservation practices such as the application of N match with crop demand, application of N fertilizer based on the natural pattern of soil fertility, an application within the root zone rather than on soil broadcasting, and applying fertilizer close to crop need. But all types of N fertilizer with coatings could delay its dissolution capacity and in turn reduce N_2O emission.

Leaf colour chart can be used for synchronized N application with crop demand to reduce GHG emission. Application of N based on the LCC method reduced the N_2O emission in wheat and rice fields. At LCC < 4, application of 120 kg N per hectare decreased 16% of N_2O emission and 11% of CH_4 over conventional application of urea in rice. The GWP were 13.692 and 12.395 kg CO_2/ha in conventional and LCC < 4 N application, respectively (Bhatia et al. 2013). They also added that, in the rice-wheat system, GWP reduced by 10.5% for LCC-based urea application. Soil fertilized with nanofertilizer N (NH4+ form) with zeolite (carrier) recorded lower N_2O emission (1.8 mg/m2/day) than conventional fertilizer (2.7 mg/m2/day). Soil fertilized with NO3 form of N revealed lower CH_4 emission of 34.8 mg/m2/day than conventional fertilizer (36.8 mg/m2/day) (Pathak 2015). Legume-based cropping system also contributes to reducing the N_2O emission. Legumes naturally fix the high amount of N through the process of BNF.

1.7 Mitigation of Carbon Dioxide Emission

CO_2 is emitted into the atmosphere in several ways. Energy factors by fuel usage are the largest CO_2 emission source. The main strategy to lower CO_2 includes developing low C fuel or biofuel and reducing fuel usage and sequestering C through natural ways. Practically C can be stored by sequestration in soil and vegetation. According to Burney et al. (2010), intensive agriculture improved the C sequestration because of the high amount of crop residues of root biomass and exudates returned to the soil as C source. Benbi and Brar (2009) reported that intensive agriculture enhanced the soil organic C by 38% by reducing CO_2 emission in the 25 years study of the Indian situation. The indirect emission of CO_2 can be reduced by improving the use efficiency of energy-based inputs like fertilizers, pesticides, and irrigation. Once SOC is sequestered, it must be retained and should not return to the atmosphere quickly, i.e. called C sequestration, and it depends on the mean residence time (MRT) of C. It is the long-term storage of C in the soil as well as the capacity of soils to remove CO_2 from the atmosphere. There are five important global C pools. Among those, oceanic pool (38,000 pg) is the largest and then geological pool (5000 pg), coal pool (4000 pg), oil and gas pool (500 Pg), pedological pool (SOC 2500 pg), biotic pool (560 pg), and atmospheric pool (760 pg). According to Lal (2004), the average lifetime of C in the atmosphere is 5 years, vegetation is 10 years, soil is 35 years, and sea is 100 years. The CO_2 is fixed by plants, (leaf litter, roots, and root exudates), and the activity of soil fauna transforms these substrates into more resistant organic components called humus which is a highly resistant material (Fig. 1.4). Management of soil to perfect C storage includes minimum tillage, crop residue, mulching, applying slow degradable C such as biochar, and other C sequestration measures.

The MRT of SOC depends on the SOC pool and flux which may be influenced by soil management and land use. According to Lal (2016), the MRT of SOC is affected by so many factors, i.e. the stabilization of soil C in soil aggregates, clay-humus complex formation, subsoil storage, slower microbial decomposition, the creation of high energy bonds, the formation of recalcitrant substances, and complexation into long-chain polymers. Benbi et al. (1998) reported that application of FYM along with NPK to rice sequestered on an average 0.17/C/ha/year. Pathak et al. (2015) reported that organics combined with fertilizers sequestered more C. According to Benbi et al. (2012), 8–21% of the occluded C is sequestered in the soil based on soil type and climatic conditions. The addition of crop residues, animal manure, and compost improves the formation of macroaggregates and stores inside the aggregates (Benbi and Senapati 2010; Kakraliya et al. 2018).

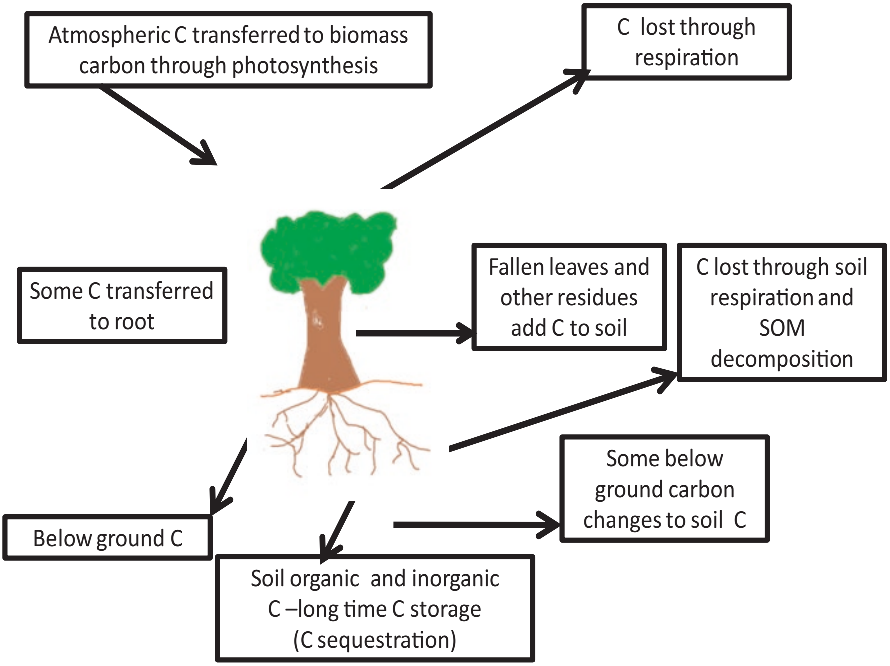


Fig. 1.4 Process of C sequestration

Soil under rice-based system is found to sequester 70% more C than a maize-wheat system. West and Post (2002) also revealed that the change of tillage from conventional to no-till could sequester 57–74 g C/m2/year.

The effect of crop rotation on C sequestration depends on crop species and crop residue management. Cropping systems and choosing of crops also play a role to improve SOC which is a way to remove C from atmosphere and store for a long time. Introducing perennial crops to crop rotation enhances the SOC stock and quality (Pellegrino et al. 2007; Meena et al. 2015c). Including legume in the cropping sequence does not have a significant effect on C sequestration due to its low biomass production. However, the highest potential of this type of cropping sequence with avoidance of Nous fertilizer consequently reduces the other GHG, i.e. N_2O emission. Crop rotation involving legumes is included in the European Union's Common Agricultural Policy's greening programme requirements with incentives encouraging the farmer's implementation. Aguilera et al. (2013) reported an average SOC sequestration rate of 0.27 Mg//ha/year for all types of cover crops in a meta-analysis of Mediterranean cropping system. Long-duration crops will sequester high C and restore soil fertility. The effect of short-duration crops does not have any significant effect with short-term studies. However, the positive effect of crops on C storage is observed with long-term studies (>15 years) if crop biomass is properly recycled. Use of crops has been considered as a means to improve labile C pools by incorporating plant biomass. Legume cultivation in yearly rotation reduces to greenhouse gas emission from N fertilizer manufacturing.

According to Bama et al. (2017a), bhendi-maize cropping sequence registered higher SOC stock of 11.24 t/ha/year (Fig. 1.5). They also stated that, irrespective of manures and cropping sequence, minimum tillage recorded higher SOC stock of 10.92 t/ha/year than conventional tillage of 10.72 t/ha/year. Mulching with 75% recommended dose of fertilizers and 25% N through organics revealed higher C stock than mulch with 100% recommended dose of fertilizers. They also added that, in the cotton green gram cropping sequences, irrespective of mulching and fertilizer treatments, minimum tillage recorded higher SOC content (5.15 g/kg) than conventional tillage (5.0 g/kg). Among the manurial treatments, the higher SOC of 5.30 g/kg was recorded in the treatment with mulch +75% recommended dose of N through fertilizers and 25% N through organics.

The soil C stock value indicated the capacity of the soil to hold C. Bama et al. (2017b) reported in another study that a higher value of total C is recorded in bhendi-maize+cowpea-sunflower sequence that might be due to the addition of legume crop sequence (Fig. 1.6 and Table 1.3). The lowest TOC was recorded in cotton and sunflower cropping sequence (7365 mg/kg) due to the exhaustive nature of crops. Smyrna (2016) also reported the same trend of the result.

According to Bama and Babu (2016), forages particularly grass-type fodder contribute to C sequestration in terms of a long-time C storage from roots, i.e. belowground portion, and it can saturate C level quickly wherever the climate change mitigation is essential. Among the various forage crops, Cumbu Napier hybrid grass removed higher C removal by biomass, and among the sources, farmyard manure application sequestered more C in the belowground. Bama et al. (2017c) reported that zero tillage recorded higher C stock value of 13.12 t/ha followed by minimum tillage (12.79 t/ha) (Fig. 1.7).

Bama and Somasundaram (2017) revealed that green manure-brinjal-sunflower cropping sequence registered higher soil organic C value (7257 mg/kg). Irrespective of the cropping system, organics (100%) alone revealed higher SOC (7143 mg/kg) (Fig. 1.8).

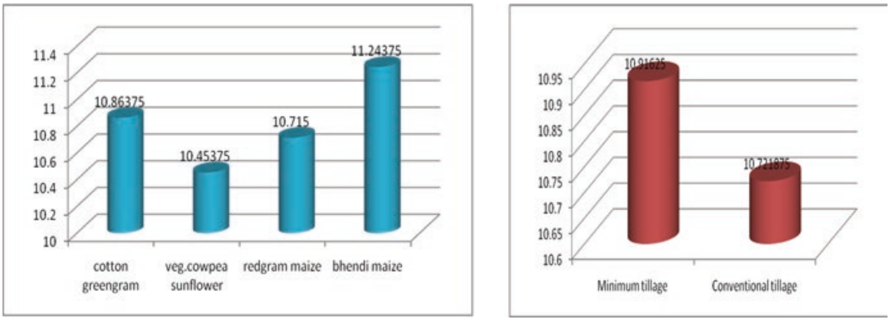


Fig. 1.5 Soil C stock as influenced by different cropping sequences and tillage practices (Bama et al. 2017a)

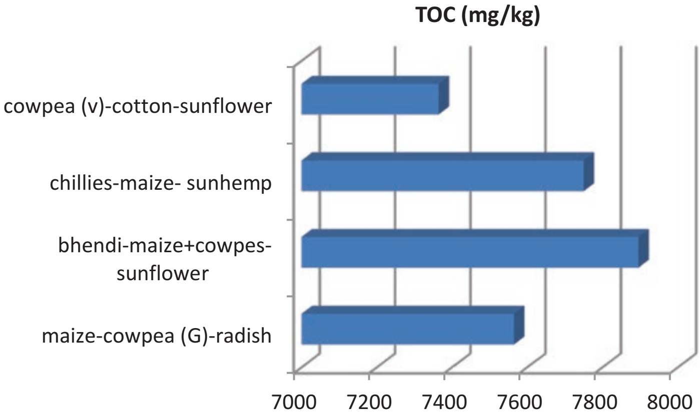


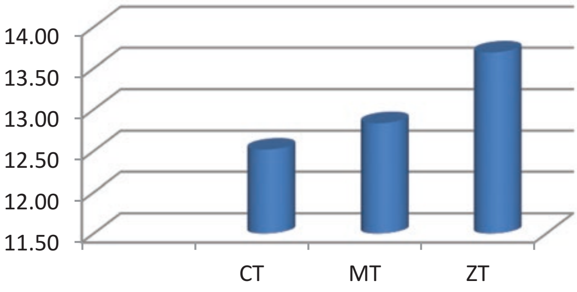
Fig. 1.6 Influence of different cropping sequences on total soil C (Bama et al. 2017b)

Table 1.3 Influence of different cropping sequences on total soil C

Cropping pattern	TOC (mg/kg)
Maize-cowpea (g)-radish	7565
Bhendi-maize+cowpea-sunflower	7895
Chillies-maize-sunn hemp	7750
Cowpea (v)-cotton-sunflower	7365
CD (5%)	425

Bama et al. (2017b)

Fig. 1.7 Soil C stock (t/ha) under tillage practices in a cotton-maize cropping sequence (Bama et al. 2017c). *CT* conventional tillage, *MT* minimum tillage, *ZT* zero tillage



CT -conventional tillage

MT -minimum tillage

ZT -Zero tillage

Bama (2014, 2017) reported a drastic improvement in the organic C status of the soil by the application of organic manures in the Cumbu Napier hybrid grass grown soil, i.e. higher organic C content of 1.28% in the FYM applied on N equivalent basis than other organic sources over an initial C status of 0.71% only. The increase in organic C is attributed to direct addition of organic manure in the soil which

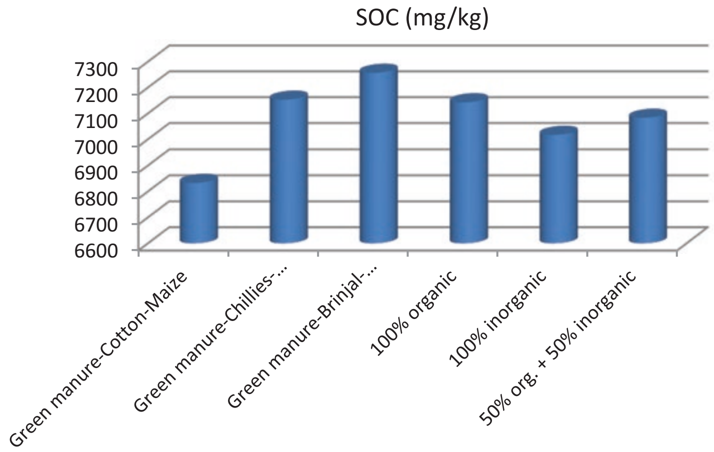


Fig. 1.8 Influence of intensive cropping and fertilization on SOC (mg/kg) (Bama and Somasundaram 2017)

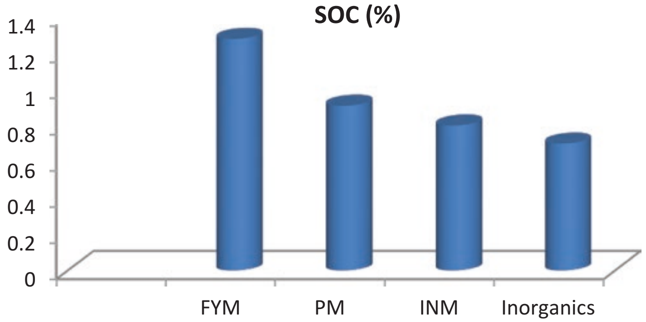


Fig. 1.9 Soil organic C as influenced by Cumbu Napier grown soil under different nutrient sources (Bama 2017)

stimulated the growth and activity of microorganisms and also due to better root growth resulting in the higher production of biomass, crop stubbles, and residues. Soil organic C as influenced by Cumbu Napier grown soil under different nutrient sources is given (Fig. 1.9).

Bama and Babu (2016) reported that Cumbu Napier grass had higher C sequestration potential of above-ground biomass which removed 336.7 t CO_2/ha than multicut fodder sorghum (148.7 t CO_2/ha) (Fig. 1.10 and Table 1.4). They also reported that, the belowground biomass C removal in Cumbu Napier grass (7.73 t CO_2/ha) from the atmosphere than Lucerne (4.21 t CO_2/ha). The soil physical properties and microbial populations were also favourable in the grass-type fodder. In addition, the Cumbu Napier fodder crop stored 9.2 g/kg of SOC over initial SOC status of 6.5 g/kg, followed by multicut fodder sorghum which accumulated 8.7 g/kg. The FYM

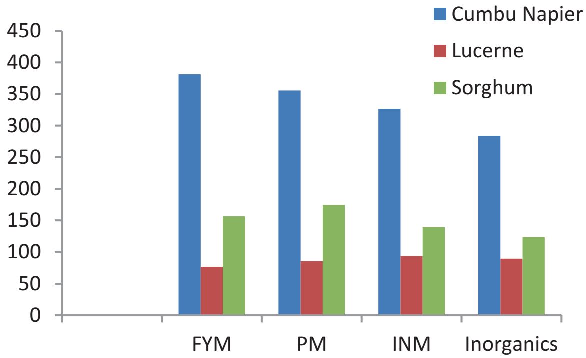


Fig. 1.10 Carbon dioxide removal (t/ha/3 years) by the above-ground biomass of various fodder crops (Bama and Babu 2016)

Table 1.4 Carbon dioxide removal (t/ha/3 years) by the above-ground biomass of various fodder crops

Treatments	Cumbu Napier	Lucerne	Sorghum	Mean
S1-FYM	381.3	76.7	156.5	204.8
S2-PM	355.4	85.5	174.5	205.1
S3-INM	326.4	93.9	139.7	186.7
S4-inorganics	283.7	89.6	123.9	165.7
Total	336.7	86.4	148.7	

FYM farmyard manure, *PM* poultry manure, *INM* integrated nutrient management

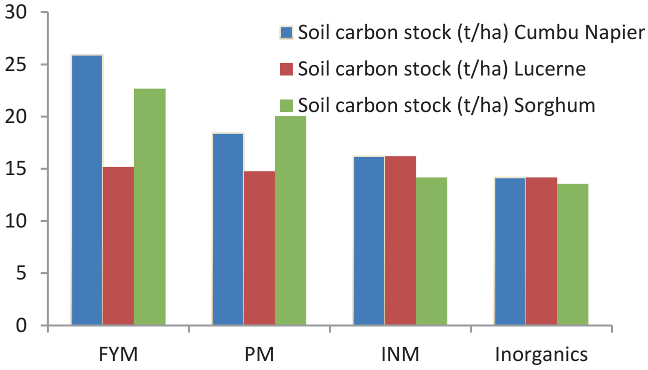


Fig. 1.11 Soil C stock (t/ha) as influenced by various fodder crops under different nutrient sources (Bama and Babu 2016)

application to Lucerne and Cumbu Napier hybrid grass improved the soil quality (Bama 2016; Bama et al. 2013; Meena and Yadav 2015; Kumar et al. 2018).

The soil C stock worked out to be 18.63 t/ha/year in Cumbu Napier grass than by multicut fodder sorghum (17.62 t/ha) (Fig. 1.11).

Judicious management of nutrient is important for SOC sequestration. Generally, organic usage enhances the SOC pool than the inorganic fertilizers. Compton and

Boone (2000) reported that the long-term application of manures increased the SOC pool and improved the aggregation. The role of conservation tillage on increasing SOC greatly enhanced with organic manure amendments.

Smith et al. (2000) reported that application of manure to cropland enhanced the SOC pool than in pasture land. Majumder et al. (2008) observed the maximum amount of organic C in the recommended dose of fertilizer with FYM treatment due to high biomass production. Though many studies have been done by scientists on SOC, the analytical procedures are still questionable with regard to C sequestration. Bama and Latha (2017) enforced the standardization of analytical methods for C sequestration studies and explained about the role of land use and management on soil C fractions. Bama (2018) reported the analytical procedures for C sequestration studies.

For climate change mitigation, agroforestry is the good option, because of the undisturbed condition and long-time C storage in biomass. Lal (2004) observed the effect of agroforestry with *Sesbania* on the SOC pool and C sequestration rates (ranges 4–9 mg C/ha/year). He added barren land can store SOC at 20 t/ha. Among different land use, the forest has the highest potential to mitigate, followed by agroforestry, plantations, agriculture, and pasture.

The conservation practices, viz. reduced tillage, crop residue management, agronomical practices in crops, and cover cropping in plantation crops, have other benefits to improving soil properties, i.e. chemical and biological qualities, and crop productivity enhancement besides improving Cn sequestration.

The increased physical stabilization of SOC by the reduced tillage was reported by Plaza-Bonilla et al. (2010). An annual increase of 1% SOC was reported with no-tillage in Mediterranean croplands (Aguilera et al. 2013; Gogoi et al. 2018; Meena and Yadav 2014), and it is above the 0.4% target of recent initiative on sustainable soil conservation (4 per mille concept). In the semiarid region, no-tillage fixed 0.5 mg C/ha/year and recommended tillage practice observed with only 0.06 mg C/ha/year. However, contrary to that, a steady increase of sequestration may not be true because the accumulation rate may change in the long term (Alvaro-Fuentes and Paustian 2011). Reduced tillage is an acceptable practice to mitigate climate change. Even no-tillage required herbicide application to control weeds which may cause environmental pollution. The effort is required to promote no-tillage with reduced use of herbicides.

Research in tropical forests has reported that 20–80% of fine roots are colonized by AMF (arbuscular mycorrhizae fungi). The collocation to the AMF and their soil C contribution is based on one of the compounds produced by AMF, i.e. glycoprotein called glomalin. The concentration of glomalin in soil ranges from 2 to 15 mg/g of soil. The glomalin improves soil aggregation thereby protecting C from degradation in soils. Rillig (2004) reported that mycorrhizal fungi are an important part of the SOC pool in addition to C sequestration by soil aggregates stabilization. The role of AMF in mitigating climatic change has been reviewed by Staddon et al. (2002). Studies conducted with C14 labelling revealed that photosynthate is transferred from host plants to AMF fungi within hours after labelling (Johnson et al. 2002; Layek et al. 2018; Meena and Lal 2018). The AMF form root colonies with more than 80% of the plant species. It will make a symbiotic relationship with higher plant roots. Hyphae radiate out of roots and spread with the long mat. These colonies form a pathway for transfer of photosynthetic C and to the soil. Since glomalin takes decades to centuries for decomposition, it can improve C sequestration rate in soil.

Application of biochar to agriculture paved the way for storing C for a long time undistributed in the soil, and researches have reported that biochar will reduce the greenhouse gas emissions. Biochar is a biologically very tightly fixed C which is not easily degraded by the soil microbes. The C present in biochar has an aromatic form which is highly resistant to decomposition (Purakayastha et al. 2015; Meena et al. 2017b). Biochar is a highly caseous pyrolysed product of biomass. Purakayastha et al. (2015) revealed that CH_4 emission from rice soil significantly reduced with the application of cornstalk biochar. Furthermore, biochar application improved the methanotrophic bacteria rather than methanogenic which induce CH_4 emission.

Galinato et al. (2011) reported the effect of biochar on N_2O that it not only reduces the cumulative N_2O emission (52–84%) but also NO (47–67%) compared to mineral fertilizer. In India, a total of around 500 MT of residues are produced; if it is converted into biochar, about 50% of C can be captured because the soil is determined to hold more (1100 Gt) C than the atmosphere (750 Gt) and terrestrial biosphere (560 Gt). The global flux of CO_2 from soil to atmosphere is about 60 Gt of C per year due to decomposition of soil and microbial respiration. Most C in the terrestrial biosphere (86% of above-ground C) is in forest green cover; also, 73% of the soil C is in forest soil.

The mitigation potential of organic farming on three greenhouse gases given by Kotschi and Muller-Samann (2004) showed that permanent soil cover, reduced soil tillage, restriction of fallows in semiarid regions, and diversification of crop rotations including fodder production reduce the CO_2 and N_2O emissions. Use of manure and waste, recycling of municipal waste and compost, biogas slurry, reduction of fodder import, and restriction of livestock density reduce the CH_4 emission. In addition to that, restriction of nutrient input, inclusion of leguminous plants, consumption of regional products, and shift towards organic vegetarian products reduce the CO_2 and N_2O release.

1.8 New Concept for Climate Change Mitigation

The new concept, i.e. 4 per millie, was started during the Conference of Parties 21 (COP21) at Paris with an intention to increase SOC stocks by 0.4% per year as compensation for anthropogenic emission of greenhouse gases (Fig. 1.12).

According to Batjes (1996), annual GHG emission from fossil C is 8.9 gigatonnes, and global estimate of soil C stock to 2 m of soil depth is 2400 gigatonnes. If we consider our world land area to be 149 million cm2, C storage would be estimated at 161 tonnes per hectare. So 0.4% equates 0.6 tonnes of C per hectare per year to be sequestered. This 0.4% cannot be applied everywhere since soils vary in their storage capacity. Based on the research work published, SOC sequestration

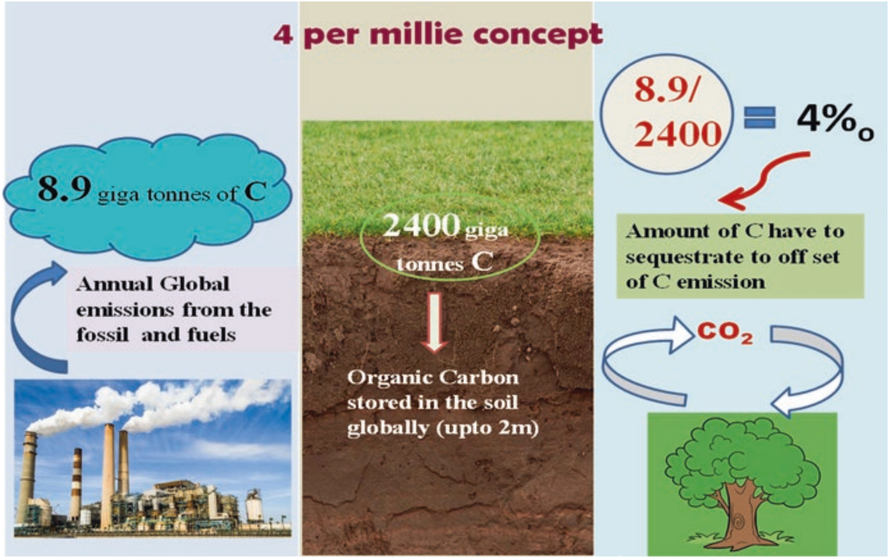


Fig. 1.12 New concept for climate change mitigation (Batjes 1996)

rate of 0.2–0.5 tonnes C per hectare is feasible with best management practices such as reduced tillage, inclusion of legumes in the crop cycle, cover crops, application of organic manures, reduction of fertilizer use, and crop residue mulching. Chen et al. (2015) reported that increasing the SOC level is possible due to improved management practices. Some researchers suggest that the soil has a limited holding capacity to store C, i.e. called C saturation. There is a hypothesis, i.e. a critical level of C and C saturation, which depends on soil texture and climatic condition (Stockmann et al. 2015; Meena et al. 2018b).

1.9 Implementation Policies for GHGs Reduction

To mitigate climate change, India has started a capacity building programme on research and development in climate resilient agriculture called National Innovations on Climate Resilient Agriculture (NICRA) which aims to train agricultural scientists in climate change adaptation strategies. The following researchable issues are to be taken up by the scientist to mitigate climate change (Pathak 2015).

Policy Issues

- Establishing an institutional mechanism for data collection and management of GHG inventory at state and national levels
- Linking all government subsidies, viz. fertilizer resistibly and other agri-inputs with GHG mitigation
- The inclusion of mitigation technologies in developmental schemes at national- and state-level plans

- Developing a C credit programme and by innovative payment mechanisms
- Enhancing research funding to do focus research on climate change mitigation through creating a separate wing in all funding agencies
- Capacity building to officials and awareness creation at the public for best management practices which mitigate climate change

Future Thrust

- Developing a feasible methodology for measuring GHG emission
- Developing low C and N emission agricultural technologies
- Methodologies for reducing GHG emission from livestock by better management of feeding practices
- Assessing mitigation co-benefits of climate change mitigation technologies
- Assessing the cultural and economic feasibility of greenhouse gas mitigation technologies

1.10 Conclusion

The soil is the key component of the agricultural production system. Hence soil health needs to be relooked in light of projected climate change for sustainable agricultural productivity. Evaluation and dissemination of climate resilient soil management strategies are required to mitigate the probable impacts of climate change on agriculture. Due to continuous climate variations, greenhouse gases are produced and in turn created global warming potential. The greenhouse gases, viz. CH_4, N_2O, and CO_2, are important sources from agriculture. The main source of CH_4 emission is from rice soils due to continuous submergence and fresh organic matter addition. N_2O is emitted to the environment by the continuous use of Nous fertilizer. The source for CO_2 is from the soil through tillage operation, land use change, and cropping system. The mitigation strategies for CH_4 from rice soil are through the adoption of water management by alternate wetting and drying practice. The N_2O emission can be reduced by less usage of N fertilizer, nitrification inhibitor, LCC-based N application, and inclusion of legume crops in the crop rotation by promoting biological N fixation and reducing the N use. The CO_2 emission from soil can be reduced by selection of crops with high C harvesting potential especially belowground C storage of high root biomass, no-tillage, organic soil cover, crop diversification, proper nutrient management by including more of organics, improving AMF count, application of biochar, etc. The new initiative started during COP(21) is also insisting the soil C storage rather than thinking the other methods to reduce the GHG emission. The mitigation options to manage the climate change are available either alone or in combination in the farmer fields needs governmental support. Policies and incentives should be evolved that would encourage the farmers to adopt mitigation options, improve soil health, and use water and energy more efficiently.

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Strategies to Practice Climate-Smart Agriculture to Improve the Livelihoods Under the Rice-Wheat Cropping System in South Asia

2

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Abstract

The rice-wheat cropping sequence (RWCS) is the world's largest agricultural production system occupying around 12.3 M ha in India, 0.5 M ha in Nepal, 2.2 M ha in Pakistan, and 0.8 M ha in Bangladesh; and around 85% of this area falls in the Indo-Gangetic Plain (IGP). It is energy, labor, and capital intensive, favors global warming, and ultimately has a detrimental effect on the natural resources and soil biodiversity. Furthermore, the rice-wheat cropping sequence has a number of sustainability issues, viz., declining land and water productivity, poor soil health, and arising micronutrient deficiency which is an alarming issue. Integrated approaches must be developed for improving the declining livelihoods in the region. The changing climate and its consequences are complicating the situation of the available natural resources, viz., water, soil, atmosphere, etc. Carbon (C) and water footprints need to be identified in the currently practiced rice-wheat cropping sequence for filling the gaps to improve livelihoods by one or other means. Resource conservation technologies (RCTs) partition greater fraction of water from unproductive evaporation to the desired transpiration which is further reflected on the higher grain yields. Transpiration causes a greater inflow of water and nutrients which ultimately increases the grain yield with lesser consumption of irrigation water, which further increases water productivity. There is a need to focus on the issue to sustain the rice-wheat productivity in South Asia. This book chapter is focused on all the strategies to practice climate-smart agriculture for improving livelihoods in South Asia, which include irrigation based on scheduling, precision laser leveling, direct seeded rice (DSR), mechanical transplanting, crop diversification, short-duration crop varieties, and delaying transplanting time, and reevaluate their effect on water and land productivity under divergent soil textural classes under different climatic conditions in South Asia. There is a need to come out with an integrated package for the farmers depending upon their conditions. Delineation of the residual consequence of used RCT on available moisture during the intervening periods is there, as it affects the performance of intervening crops and certainly adds to the livelihood of the farmer. The aim of this chapter is to review different technologies and their impact on land and water productivity and thereby try to come up with some integrated approach for improving livelihoods of farmers of the region. Therefore, scientists must be very careful while advocating any single RCT or a set of RCTs to the farmers with a must consideration of their social, financial, and geological conditions for enhancing both land and water productivity in South Asia.

Keywords
Climate-smart agriculture · Rice-wheat cropping sequence · South Asia · Water productivity

Abbreviations

AWD	Alternate wetting and drying
CA	Conservation agriculture
CE	Carbon equivalent
CF	Carbon footprint
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CSA	Climate-smart agriculture
DSR (ZT)	Direct seeded rice under zero tillage conditions
DSR (CT)	Direct seeded rice under conventional tillage conditions
ET	Evapotranspiration
FIRBs	Furrow-irrigated raised beds
GEU	Gypsum-enriched urea
Gt	Gigatons
IGP	Indo-Gangetic Plain
INPM	Integrated nutrient and pest management
LCC	Leaf color chart
MDG	Millennium development goal
MT (P)	Mechanical transplanting under puddled conditions
MT (ZT)	Mechanical transplanting under zero tillage conditions
MTR	Mechanical transplanting of rice
N_2O	Nitrous oxide
NOCU	Neem oil-coated urea
NUE	Nitrogen use efficiency
PAU	Punjab Agricultural University
PGEU	Phosphogypsum-enriched urea
PM	Particulate matter
ppm	Parts per million
PTR	Puddled transplanted rice
RCTs	Resource conservation technologies
RWCS	Rice-wheat cropping sequence
SEU	Sulfur-enriched urea
SOC	Soil organic carbon

SOM	Soil organic matter
SPAD	Soil plant analysis development
SRI	System of rice intensification
SSNM	Soil-specific nutrient management
SSRM	Site-specific residue management
STCR	Soil test crop response
Tg	Teragram
WP_I	Irrigation water productivity
ZEU	Zinc-enriched urea
ZT	Zero tillage

2.1 Introduction

The rice (*Oryza sativa*)-wheat (*Triticum aestivum*) cropping sequence (RWCS) is the world's largest agricultural production system occupying around 12.3 M ha in India, 0.5 M ha in Nepal, 2.2 M ha in Pakistan, and 0.8 M ha in Bangladesh; and around 85% of this area falls in the Indo-Gangetic Plain (IGP) (Bhatt et al. 2016). South Asian agriculture has undergone significant growth during the last five decades because of scientific and technological advancements in agriculture called "Green Revolution" owing to policy interventions and scientific workforce (Bhatt et al. 2016). The Green Revolution we inherit in the twenty-first century in South Asia represents some of the greatest achievements of human civilization. Crop improvement and production technology advancements have greatly increased the agricultural production; but the outcome of Green Revolution is poor on many counts like natural resource management (NRM), climate resilience, and nutritional quality (Olk et al. 1996). Conventional agriculture has resulted in a decline in factor productivity, natural resource base, soil health, and water availability, groundwater depletion, and increased susceptibility to diseases and pests as well (Aggarwal et al. 2004; Bhatt et al. 2016; Meena and Meena 2017). Hence, the current production scenario represents some of the greatest threats to agricultural sustainability. Today, prevailing global food systems contribute around one-third to the global warming by producing different greenhouse gases (GHGs), viz., methane (CH4), nitrous oxide (N2O), and carbon dioxide (CO2). Seventy percent of all water withdrawn from aquifers, streams, and other groundwater resources is used for agriculture often at unsustainable rates. Furthermore, conventional agricultural systems have contributed significantly to land degradation, soil health decline, as well as the destruction of natural habitats and biodiversity at large (Paul et al. 2014; Dass et al. 2016a, 2017b). Therefore, indeed the foundation on which current production systems stand is becoming fragile in a holistic manner. In a nutshell, current agronomical production technologies are not in place to sustain food security and natural resource management. On another hand, the millennium development goal (MDG) of quality grains for each must be generated through climate-smart and sustainable agriculture so as to improve global health, more particularly of developing nations.

In South Asia, the conventional cereal-based production systems (rice-wheat and rice-rice) are facing yield stability turndown causing a severe challenge for agricultural and environmental sustainability (Prasad 2005). The conventional rice production technologies are capital, labor, water, and energy intensive, which further reduces their adaptability because of lesser grain yields (Kaur et al. 2015; Pooniya et al. 2018; Ashoka et al. 2017). As per one estimate, rice, wheat, and maize (*Zea mays*) land productivity needs to be increased by about 1.1, 1.7, and 2.9% per annum, respectively, for providing ensured nutrition to the growing population of South Asia (Pfister et al. 2017; Sofi et al. 2018).

Short-duration crop cultivars, delaying transplantation time, and crop diversification are the key components, which play a significant role in improving/declining both land and water productivity in the rice-wheat system (Pooniya et al. 2017). Presently, there is a need to switch over to holistic integrated methodological approaches involving innovative agronomic management principles with climate-smart agriculture (CSA) (Dass et al. 2016b). The key drivers for the innovative agronomic interventions are declining factor productivity, groundwater depletion, deteriorated quality, and the ever-increasing cost of irrigation. However, degraded soil health, climate change effect on crop productivity, rising cost and declining availability of agricultural labor, rapidly expanding agribusiness sector associated with mechanization and value addition, and policy fatigue are also some other contributing factors. Some of the innovative agronomic practices such as conservation agriculture (CA) with judicious crop rotations and site-specific residue management (SSRM) are leading the path of transition toward sustainable food production systems (Paul et al. 2014; Dass et al. 2016b; Choudhary and Suri 2018; Meena et al. 2015d).

Different resource conservation technologies (RCTs) were being adopted at around 5.6 million ha area in South Asia (National Agricultural Research and Extension Systems (NARES) (GOI 2016). Likewise, CA is being promoted to improve nutrient and water use efficiency (WUE). In India, the overall savings is USD 164 million with an investment of only USD 3.5 million on zero-tillage (ZT) technology with an internal rate of return of 66%. In addition to the savings on production inputs, CA-based management practices have other potential benefits such as natural resource conservation, reduced emission of GHGs, and better resilience to climatic extremes. However, moving from conventional to CA-based technologies involves a paradigm shift not only in key elements but also in approaches to develop component technologies of cultivar choice, nutrient, water, weed, and pest management while optimizing cropping systems (Bhatt et al. 2016; Mitran et al. 2018). Different agroecological methodologies, viz., system of rice intensification (SRI), are being promoted to manage plants, soil, water, and nutrients to improve the overall production potential in the region (Choudhary and Suri 2018). The SRI comprises three essential principles: planting young seedlings, planting single seedlings, and applying “minimal irrigation water” that keeps the soil just at and below saturation (Dass et al. 2016b). All the recommendations for drainage and irrigation need to be revised as per different soil textural classes, and different integrated approaches comprise one or more than one technology needed to be adjusted for having better livelihoods for the farmers. In SRI, increase in yield is possible because of young seedlings transplanted in rows; but still, farmers are not accepting it because of labor-intensive transplanting operation, precise water and input management, and higher labor cost. Like SRI technology, the time demands a thorough understanding and integration of different technologies as a package for various production systems. The current farmer dilemma and multifaceted technology delivery system highlight the need for characterization area and a cropping system suitable for "integrated package of production technologies" and subsequently technology targeting. It also demands wider emphasis and integration between leaders in different institutions advocating stand-alone production technologies.

From the last half century, crop production meets the landmarks because of breeding new better crop cultivars, new pesticides/insecticides, better fertilization and irrigation facilities, etc. Feeding the ever-increasing population with ever-decreasing/diminishing resources, viz., land and water, is the main challenge in front of the agricultural scientists under the present scenario of climate change. In the developing countries like India, still agriculture is the main occupation of the rural people. Since the 1960s, world per capita agricultural production has increased by 25% with varying trends as in Asia it increases while in Africa it decreases because of many countable and uncountable factors, at a cost of environmental degradation, declined underground water table, deteriorated soil structure, etc. as crop production and sustainability entirely depend on land, water, forests, pastures, nutrients, etc. A different technique of climate-smart agriculture must be adopted in a holistic manner so as to practice sustainable agriculture by producing for the present generation but reserving the natural resources for the generations to come.

2.2 Sustainable Agriculture and Its Principles

Sustainable agriculture describes different principles which meet the need of food for the present population by using the available natural resources of land and water but also considering the future generations. The major goals of this approach are to develop economically viable agroecosystems to enhance the quality of the environment so as to keep the arable lands productive indefinitely. Thus, sustainable agriculture involves farming systems that are environmentally sound, profitable, productive, and compatible with socioeconomic conditions. Improved nutrient cycling, improved soil quality, reduced degradation of land, and integrated nutrient and pest management (INPM) techniques along with good marketing to ensure better profits are the main pillars of sustainable agriculture. Improving the soil organic matter (SOM) is the only key factor which further improves the soil physical, chemical, and biological properties in one or other ways. Improved nutrient cycles and adopted INPM techniques at the farms improve the livelihoods of the poor farmers by minimizing their input cost and at the same time getting a better price for their produce because of better quality. There are five basic goals of sustainable agriculture, viz., food security, environmental security, economic viability, social acceptability, and food safety and quality which need to be fulfilled by adopting one or a set of resource conservation technologies.

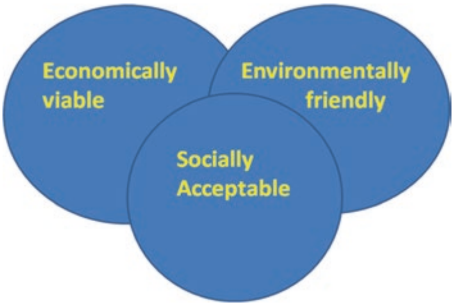

Fig. 2.1 Dimensions of sustainable agriculture

Sustainable agriculture covers different approaches which achieve an environmentally sound, economically profitable, ethically acceptable, and socially responsible form of land husbandry. Sustainable agriculture means more efficient use of arable land and water with improved agricultural practices and technologies to increase crop yield on a long-term basis without detrimental effect on the environment. Agricultural sustainability has three dimensions: ecological, economic, and social (Fig. 2.1).

Sustainable agriculture aims at judicious use of available natural resources in such a way to minimize adverse impacts on environments while providing sustained production. It is a form of agriculture system which aims to satisfy the needs of the present generation without endangering the resource base for upcoming generations. The three dimensions of sustainable agriculture are ecological, economic, and social criteria. Under ecological criteria, consideration is given to natural resources; under economic criteria, livelihoods are mainly dealt with; and social criteria entirely depend on respecting the farmers' indigenous knowledge, beliefs, and value systems in such a way to convince them for the adoption of the improved practices over theirs.

2.3 Strategies to Improve Land and Water Productivity in South Asia

The South Asia population shares 22% of the world population which entirely depends on the 3.31% of the world's land mass (SAARC country profiles 2014) for meeting their requirement of land and water. Natural and agricultural areas shifted to residential and urban areas under the impact of increasing population. Indiscriminate use of natural resources led to a situation where food production reached a stagnant stage and, even at every struggle, production not increased which further put pressure on the agricultural scientists to work out new farmer-friendly climate-smart technologies which work (Shukla et al. 2008; Lobell et al. 2008). Change in the land use trends affected all the natural nutrient and water cycles by one or other ways which need to be corrected at the earliest (Turner and Annamalai 2012; Madsen 2013; Yadav et al. 2018b). For bringing positive significant change in the present land and water use systems, a scientist has to be aware by demonstrating the new agricultural technologies in front of the farmers at the farmers' fields instead of publishing them in reputed journals for having promotions. Furthermore, there is a need to delineate the change in the land cover over the last decade for framing some new improved policies for making a change which if not acceptable by the farmers then must be imposed on them by some legal structure. For example, in Punjab, transplanting paddy after June 20 is mandatory for all the farmers from the year 2018 onward; otherwise, his nursery will be slowed down in the field. Furthermore, farmers' leaders, local politicians, and, most importantly, regional scientists who are most able to identify the research gaps and priorities in the region must be involved in the different projects. Intensive agriculture, puddling operations, lower use of fertilizers, non-adoption of INPM, etc. have resulted in the higher rate of soil nutrient depletion in South Asia, while the use of mulching; leguminous crops for biological nitrogen fixation, viz., pulses; farmyard manure; and other organic inputs is limited to a significant extent, and the reasons are many.

Land degradation led to lowered water and land productivity which further led to food insecurity. Substantiation of land degradation is widespread in Uganda as soil erosion, soil fertility mining, soil compaction, waterlogging, and surface crusting. Soil erosion and soil fertility mining are claimed the most. In some regions of Uganda, 60–90% of the total land area is affected by soil erosion. Soil fertility mining in Uganda is occurring at among the highest rates, with an estimated average annual rate of total nutrient depletion (Stoorvogel and Smaling 1990). Furthermore, the soil erosion problem needs to be attended soon to prevent bifurcation of the land and for improving the livelihoods of the farmers.

2.4 Causes of Land Degradation

In India, Punjab and Haryana states are referred to as the "Food Bowl" states which produce 50% of the national rice production (Dhillion et al. 2010). A gravity satellite named "GRACE" recently delineated those northern regions of India as facing a sharp decline in underground water (Soni 2012; Meena and Lal 2018). Rice in these states is normally flood irrigated during most parts of the season leading to declined water levels since the 1970s (Hira et al. 2004). The fall in water table particularly in central Punjab has been reported to increase from 0.2 m year^{-1} during 1973–2001 to about 1.0 m year^{-1} during 2000–2006. Majority of the blocks in Punjab are being overexploited for pumping out groundwater (Humphreys et al. 2010). The lowering of the groundwater table in the state has been resulting in an increase in the energy requirement and tube well infrastructure cost and deteriorating groundwater quality (Hira 2009). Moreover, subsurface compaction in these soils (Sur et al. 1981; Kukal and Aggarwal 2003a) (after repeated puddling of coarse- and medium-textured soils) results in poor root growth of the succeeding crops, viz., wheat, commonly referred to as "plough pan" (Kukal and Aggarwal 2003b). Plough pan with high bulk density at 15–20 cm creating aeration stress poses threat for the proper wheat root growth (Aggarwal et al. 1995; Kukal and Aggarwal 2003b; Buragohain et al. 2017). Thus, rice established through puddling operations leads to soil deterioration and environmental degradation and proves a hurdle in front of sustainable agriculture.

Another major issue related to the rice-wheat cropping sequence (RWCS) is effective management of rice crop residue, which due to high silica content is not fed to the animals and is normally burnt by the farmers. The burning of rice residues is the main adopted disposal method especially in the areas where machine harvesting is being practiced. Disposal of crop residues by burning is not a viable option due to losses of SOM and nutrients, C- emissions, intense air pollution, and reduced soil microbial activity (Kumar and Goh 2000). As per the estimates, 113.6 Mt of rice and wheat residues containing 1.90 Mt nutrients are produced every year in the IGP of India (Sarkar et al. 1999). In Punjab, about 12 Mt of rice straw is burnt annually causing 0.7 Mt of N loss apart from the emission of 70% CO2, 7% CO, 0.66% CH4, and 2.09% N2O (Singh et al. 2010). Dobermann and Fairhurst (2002) reported that nitrogen (N) (90%), sulfur (S) (60%), and phosphorus (P) and potash (K) (around 20–25%) of the rice straw are lost while burning. Studies (Sidhu and Beri 1989; Beri et al. 1995) have shown that incorporation of rice residues decreased grain yield of wheat from that with removal or burning, due to N immobilization attributable to the slow rate of residue decay. Residue incorporation just before rice transplanting results in accumulation of phenolic acids in soil and increases CH4 emissions under flooded conditions (Grace et al. 2003; Meena and Yadav 2015). The intensive tillage for wheat seedbed preparation breaks down the aggregates to expose soil organic carbon leading to its loss into the atmosphere (Ashagrie et al. 2007; Meena et al. 2018c).

2.5 Strategies to Improve Land Management

In order to take care of the abovesaid issues of declining groundwater and soil health and residue management in RWCS in the region, various RCTs which also manage the soil/land more preciously, viz., laser land leveling, mechanical transplanting, zero-tillage wheat, unpuddled rice, raised beds, mulching, etc., are being advocated for increasing profitability of this system by reducing structural degradation of soil and air pollution and increasing water, labor, and nutrient use efficiencies. These technologies mainly focus on three fundamental principles of conservation agriculture, viz., conservation tillage, intercropping, and use of crop residues (Jeffrey et al. 2012) as mulch and conservation irrigation (Bhatt 2015).

Conventionally, rice settled by puddling (tillage under stagnant water conditions) has an aim to have a bumper crop by minimizing the weed bank, percolation losses, etc. However, this operation not only is labor intensive (300–350 h ha^{-1}) but also results in structural deterioration of soil which certainly affects the upland wheat crop (Kukal and Aggarwal 2003a; Kumar et al. 2017b). The alternate tillage practices viz., mechanical transplanting (Raj et al. 2013), direct seeding of rice under dry (Sharma et al. 2005) and wet conditions (Rana et al. 2014) delineated to mitigate the adverse effects of puddling.

2.5.1 Mechanical Transplanting of Rice (MTR)

Mechanical transplanting in untilled soils has been shown to be a promising technology for establishing rice in Haryana with large energy and labor savings and regular plant spacing (Bhatt and Kukal 2014). This could particularly be beneficial in view of increasing labor scarcity in Punjab because of the Mahatma Gandhi National Rural Employment Guarantee Act (2007) which promises 100 days of paid work to the people from villages (Anonymous 2011). However, whether zero-tillage mechanical transplanting results in water or energy savings in comparison with the puddled transplanted rice is not established yet. There are few studies comparing water use in the puddled and unpuddled transplanted rice. Singh et al. (2001) observed that in sandy loam soil, puddled transplanted rice (PTR) consumed 125 mm lower irrigation water than transplanted rice in untilled soil. There is insufficient data on the components of water balance in zero-tillage transplanted rice and its water productivity. Moreover, the abovesaid studies while reporting the irrigation water savings do so in comparison to the farmers' practice of irrigation scheduling, who in general have a tendency to over-irrigate.

Mechanical transplanting of rice (MTR) helps in timely transplanting than any other method. Furthermore, DSR is reported with somewhat higher water productivity as DSR arrives a month earlier than mechanical transplanting (Bhatt 2015). Self-propelled transplanter produced similar grain yield as with the manual transplanting but produced significantly higher grain yield than that through direct sowing both under dry and wet conditions. This was attributed to the higher number of seedlings per hill planted through mechanical transplanter reported with a comparatively higher tiller, test weight of grains, and grain yield. Mechanical transplanting (MT) is preferred over manual transplanting even though yields in the latter are somewhat higher (4.87 t ha^{-1}) (though statistically at par) than the former (4.85 t ha^{-1}) (Pandirajan et al. 2006). MT of rice with self-propelled rice transplanter helps in getting the highest grain yields as compared to PTR and DSR (Singh et al. 2015a) as early establishment and uniform growth owing to uniform settlement of seedlings under MT significantly influence the plant height, total panicles m^{-2}, effective panicles m^{-2}, grain panicles -1, and weight of 1000 grains which finally resulted in higher land productivity (Table 2.1).

However, irrigation water productivity (WPI) of MTR plots was delineated to be greater than that of DSR plots and the same with that of PTR plots (Fig. 2.2). The higher WPI of mechanically tilled puddled plots (MT-P) than that of mechanically tilled zero-tillage plots (MT-ZT) plots was due to lower land productivity in MT-ZT plots. The WPI in direct seeded conventionally tilled plots (DSR-CT) was higher than that in direct seeded zero-tillage plots (DSR-ZT) plots, which was due to lower land productivity in DSR-ZT plots. This led to greater water feeding of DSR plots than in PTR. This resulted in lower WPI in no-tilled plots compared to the extensively tilled plots. Thus, in sandy loam soil, mechanically transplanted rice in puddled system performs similarly to conventionally transplanted rice. However, the crop yield decreased when rice seedlings were mechanically transplanted in zero-tillage soil (Bhatt 2015; Meena et al. 2014). However, Bhatt et al. (2014)

Table 2.1 Effect of different establishment methods on the different agronomic parameters

Treatments	Panicle length (cm)	Filled spikelets per panicle^{-1}	Unfilled spikelets per panicle^{-1}	Fertility % age	1000 grain weight (g)	Plant height (cm)	Chlorophyll index
MT (P)	23.0	124.8	13.1	91.4	23.9	82.4	43.9
MT (ZT)	22.3	115.9	18.3	86.6	20.8	72.8	42.6
DSR (ZT)	20.9	69.7	25.6	72.7	20.8	66.3	39.9
DSR(CT)	21.6	75.3	19.4	79.7	22.2	65.2	39.0
PTR	25.6	115.8	37.4	76.4	22.9	91.7	45.2
LSD (0.05)	2.2	16.8	10.5	6.2	1.6	5.4	2.25

Adopted from Kukal et al. (2014)

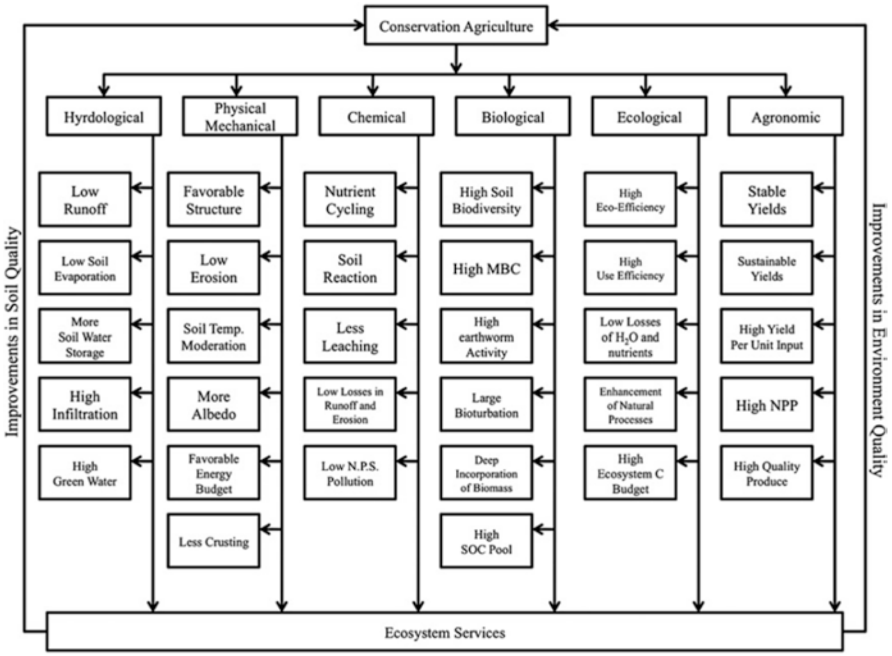

Fig. 2.2 Improved soil and environment quality through adoption of the conservation agriculture (Adopted Lal 2010)

documented reasons for non-adoption of mechanical transplanting of rice among the region's farmers even though it is found to provide good effective results more particularly in the labor shortage scenario in the comparatively shorter window period after wheat harvesting.

2.5.2 Direct Seeded Rice (DSR)

To avoid the use of considerable amount of irrigation water for puddling and continuous flooding till 15 days after transplanting in alternate wetting and drying (AWD), direct dry sowing of rice at field-capacity moisture content has been gaining ground over the last couple of years. Significant savings of irrigation water was reported under AWD at 20 kPa at 8-inch depth in a clay loam soil (Sudhir Yadav et al. 2011; Datta et al. 2017a, b). As compared to the MTR, DSR is reported with somewhat lower land productivity (Bhatt and Kukal 2017) because of already explained reasons above. This reduction in irrigation water was mainly reported due to reduced seepage losses. Sudhir-Yadav et al. (2011) reported significantly higher irrigation water productivity of DSR than PTR, but total input water productivity and ET-based water productivity were statistically at par at 20 kPa soil matric potential (SMP)-based irrigation scheduling. Very few studies related to detailed water balance characterization in DSR are reported in the literature (Bhatt 2015), particularly in coarse- and medium-textured soils. Moreover, increased irrigation water productivity of DSR could impact the irrigation water productivity of the following wheat crop, the studies on which are lacking in the literature. This technology of the DSR is site specific and cannot be suggested at all the sites as DSR proves to be a failure in the light-textured soils which is further complicated with iron deficiency and significantly higher weed population. Thus, DSR must be used with an integrated approach at heavy-textured soils. Thus, there is a need to study soil water dynamics in RWCS as a whole instead of individual crops.

2.5.3 Zero Tillage in Wheat

Direct drilling of wheat in standing rice stubbles and untilled soils (Sidhu et al. 2008) has long been advocated as a zero-tillage technique to reduce irrigation water amounts and increase water productivity (Balwinder Singh et al. 2011a). Mulch material suppresses soil evaporation (Es) (Balwinder Singh et al. 2014) and undesired plants, improves SOM by avoiding direct contact of hot sunrays onto soil surface, and decreases vapor pressure gradient which finally improves land productivity (Siddique et al. 1990; Singh et al. 2005; Meena et al. 2015c). Zero tillage improves the soil physical environment (Paccard et al. 2015) because of residue retention in the fields resulting in increased infiltration rate, water retention, hydraulic conductivity, lower soil compaction (Zheng et al. 2015), etc., while conventional tillage disperses the macroaggregates, which discloses the once concealed organic matter to microorganisms which oxidizes them into CO2 which further escapes into the atmosphere and causes global warming (Kuotsu et al. 2014; Layek et al. 2018). The contradictory results related to zero-tillage effects on soil and crops are reported in the literature (Singh et al. 2015a, b; Dhakal et al. 2015). It is mainly due to site-specific conditions including soil type, climatic conditions, and cultural practices especially for herbicide use (Singh et al. 2015a, b).

Furthermore, Jat et al. (2014) in their 7-year experiment on the clay loam soil reported higher grain yields and economical advantage of conservation agriculture (CA) which was realized after 2–3 years as the adaptation of conservation agriculture-based component technologies evolved overtime and the farmers have to settle with somewhat lower yields during the initial years. Thus, the farmers need to be convinced about lower crop yields during the initial few years for adoption of this technology for better land and input productivity at later stages. Therefore, conservation agriculture, zero tillage, mechanical tillage, and direct seeded rice are some of the resource conservation technologies which one could adopt with an integrated package of techniques for practicing climate-smart agriculture in the present era of climate change.

2.5.4 SRI System for Natural Resource Management

The pressure on land has risen from various factors, chief among them being deforestation, overgrazing, and overcultivation which caused a decline in fertility and productivity, thus aggravating poverty. In short, the tremendous increase in population and per capita economic activity has resulted in a considerable strain on our natural resource foundation. Among different initiatives taken to improve natural resource management, rice management is the most important one. Rice is the most vital food crop in most parts of the developing world including Asia besides Africa. With an increase in population growth, limited land resources, and rising demand for food, rice yields will have to increase further. Yield growth has slowed down recently, and the law of diminishing return is holding good for additional inputs. However, increase in rice production by providing higher inputs leaves a significant environmental footprint; for example, excessive use of fertilizers/pesticides could lead to environmental problems, and excessive use of water could lead to depletion of natural resources. Greenhouse gas emission and climate change issues are also there with heavily fertilized and continuously flooded rice production systems, with climate change itself likely to impact rice production negatively. Farmers in some regions are already coping with drought and water scarcity issues. Thus, future yield and growth in rice production systems have to be accomplished with less water use, less resource depletion, and less environmental degradation.

The SRI has been considered as a promising approach to increase rice production, without harming the environment. Originating in Madagascar as a way to increase the productivity of rice with a concomitant decrease in water and other input requirements, SRI is currently benefitting a large number of small farmers. The SRI and other natural resource management (NRM) technologies do have the potential to increase productivity while reducing the use of external inputs. But they are knowledge intensive and require local adaptation; hence, successful adoption by small farmers depends on proper outreach programs.

The system of rice intensification is basically an integrated approach which took into account soil, water, and nutrients in addition to managing rice plants for overall improving the livelihoods. In this regard, the work of Fr. Henri de Laulanié, SJ, who spent much of his era in Madagascar to improve livelihoods of the poor farmers and work out different combinations for growing rice, is worth mentioning. Furthermore, different methodologies developed by him were well grounded in agronomic science and helped the farmers a lot in improving their livelihoods and standards of living.

In applied terms, SRI is transplanting of 8–10-day seedlings, taking care to protect the young roots. It involves planting in a tetragonal pattern with wider spacing to give roots and canopy more chambers to grow and capture more sunlight and take up more nutrients. It maintains soil in mostly aerobic conditions and controls weeds by a simple and easy-to-use mechanical weeder that also ventilates the soil. The SRI promotes wide use of organic matter such as compost and mulch that helps to guard the growing rice plant. However, SRI can be fully carbon based also, but mineral fertilizers can also be used in case of an emergency. Generally, the best land and water productivity could also be obtained from the SRI technique. SRI in general is useful for the local farmers with local varieties and with new, improved varieties and hybrids; so they can practice sustainable agriculture in the present era of global warming. The higher requirement of labor and management is during the early stages of SRI adoption. Overall, SRI is showing promise to reduce input costs, improve water use, and produce greater yields.

Already, countries like China, Indonesia, Sri Lanka, etc. reported to be benefitting from the SRI technique. Evaluation of the SRI method of cultivation in China was performed by the China National Hybrid Rice Research and Development Center in 2000, and it was found that water intakes could be reduced by 65% with this technique as compared with conventional technique with higher land productivity of about 1–2 t ha^{-1} production. The SRI evaluation initially started on 1.6 ha with new farmers; and by the end of 2005, trials were conducted on 1363 ha, with an 84% increase in land productivity with water and cultivation cost cutting of 40% and 25%, respectively. The International Water Management Institute surveyed the water-saving potential of SRI in Sri Lanka and found that yield was increased by 44% with SRI and the income was doubled per hectare as compared to conventional method of rice cultivation.

2.6 Sustainability Issues on the Rice-Wheat Cropping System

The rice-wheat cropping system is the most prominent food production system in South Asia contributing ~45% of digestible energy (Timsina and Connor 2001). The RWCS is cultivated on ~22.5 million ha area in this region (Singh and Paroda 1994; Pooniya et al. 2018; Meena et al. 2015e). In post-Green Revolution era, the cereal-cereal production systems, mainly rice-wheat cropping system, in South Asia relied upon the unbalanced and high use of chemical fertilizers with no use of organic manures which directly posed a threat to agricultural sustainability (Paul et al. 2014; Gogoi et al. 2018). The RWCS is also the most prominent and widely adopted cropping system in India, and the farmers are frequently and intensively using this system. But due to intensive cultivation of RWCS, the region has now come to a level where yields become stagnant, micronutrient deficiencies rise, and sustainability is threatened. Regardless of gigantic growth of this cropping structure in the country during the earlier couple of decades, gossips of declining production levels, with possible decline in production in the future owing to receding resource base, have raised serious doubts about its sustainability. Important sustainability issues of RWCS in South Asia in broader sense are as follows:

- Overmining of nutrients including micronutrients
- Declining soil organic matter content
- Deterioration in soil health/soil aggregates due to wet tillage (puddling)
- Declining factor productivity especially poor response to applied nutrients
- Receding groundwater
- Waterlogging problem in canal-irrigated areas
- Low input use efficiency
- Buildup of diseases/pests and shrinking genetic biodiversity due to cultivation of fewer genotypes in rice and wheat leading to more biotic and abiotic stresses
- Lack of appropriate varietal combinations and limiting crop intensification
- Labor scarcity during the optimum period for transplanting paddy

- Changing climate with more climate variability especially in wheat leading to severe heat stress in subtropical arid agroecologies of RWCS
- Conventional puddle transplanted rice sequence resulting in the production of GHGs, viz., methane (CH_4) and nitrous oxide (N_2O)
- Buildup of herbicide resistance in *Phalaris minor* and other weed flora

Continuous cereal-based cropping systems have led to resource base degradation and production vulnerabilities at large with contaminated plant-soil-water continuum. Population pressure, climate change threats, and global trade are also challenging the sustainability of South Asian agriculture. The irrigated ecosystems have different kinds of production vulnerabilities which are the limiting factors for our national food security, and they are the threats to our national agricultural economy and rural livelihoods as well. In spite of tremendous agricultural growth during the past, reports of unsound production levels and stagnation in the productivity of major crops and cropping systems because of receding resource base and climatic variabilities have resulted in a question mark about their sustainability (Prasad 2005; Singh et al. 2011a, b). Promotion and adoption of eco-friendly practices, viz., high-yielding crops/cultivars; crop diversification imbedded with legumes; integrated nutrient, weed, disease, and pest management approaches; water-efficient crops/cultivars; climate-smart resource conservation technologies; etc. on a scale-neutral to niche area and site-specific basis would definitely address the emerging agrarian threats for agricultural sustainability (Choudhary and Suri 2014; Paul et al. 2014; Yadav et al. 2017c). Broadening of RWCS with other crops could be an important pathway to solve many problems. The policy changes would also be needed to encourage legume interventions in the rice-wheat sequence for improving sustainability and soil health (Pooniya et al. 2018; Verma et al. 2015a). Other agronomic interventions to overcome production vulnerabilities in RWCS are as follows:

- Inclusion of short-duration summer legume crops and their residue recycling
- Balanced fertilization according to soil and crop needs on a localized basis like soil test, STCR, SSNM, nutrient expert, LCC, SPAD value, and GreenSeeker
- Use of farm yard manures, biofertilizers, and green manuring
- Use of slow-release N fertilizers, viz., gypsum-enriched urea (GEU), phosphogypsum-enriched urea (PGEU), sulfur-enriched urea (SEU), zinc-enriched urea (ZEU), and neem oil-coated urea (NOCU)
- Nitrification inhibitors, i.e., N-Serve, dicyandiamide
- Adoption of resource conservation technologies like conservation agriculture, ZTR, DSR, furrow-irrigated raised bed (FIRB), and alternate furrow irrigation system
- Switching over to direct seeded rice and adoption of SRI in small and marginal farm holdings
- Integrated crop management practices with respect to weeds, diseases, nematodes, and pests
- Improved institutional credit facilities and extended availability of quality seeds and other agro-inputs

- Precision water management to improve water productivity and use efficiency
- Crop and varietal diversification with legumes and high-value cash crops for better farm profitability and rural livelihoods to create ample employment generation and check rural migration
- Integrated farming system modules for small and marginal farmers

2.7 Climate Change and Its Mitigation in the Rice-Wheat System

Climate change is responsible for increased air temperatures, erratic rainfalls, and increasing sea levels because of emission of GHGs, viz., CO_2, N_2O, and CH_4. This resulted in further continued changes in different weather parameters which affect the agricultural production by one or other means which on the other hand increased the prices of eatables. In a summarized way, the following are the consequences of global warming:

1. **Water cycle**: Because of global warming, there were frequent floods and droughts observed in different pockets of the region which further affected the agriculture by altering soil-plant-moisture interphase.
2. **Heat**: Over the next three to five decades, average temperatures will likely to increase by 1.0 °C. Global warming certainly piles up frequency of heat waves and warm nights with lesser frost days, higher respiration rates, and lower grain filling time in plants and longer growing season in temperate zones.
3. **Crop biodiversity**: Wild genotypes with important genes will be certainly affected which further on the long run certainly affects the different breeding programs operated in different regions of the country for evolving temperature- and salt stress-tolerant crops.
4. **Carbon dioxide (CO_2)**: The CO_2 concentrations will increase to about 450 parts per million (ppm) by volume over the next three to five decades. The CO_2 response is expected to be higher on C_3 species (wheat, rice, and soybeans), which account for more than 95% of world's species, than on C_4 species (corn and sorghum). The C_3 weeds have responded well to elevated CO_2 levels, symbolizing the potential for increased weed pressure and reduced crop yields.

Greenhouse gases are contributing to global warming which further affected the agricultural production in one or other ways. New technologies, viz., soil test-based fertilization, direct seeded rice, slow-release fertilizers, etc., will certainly hold the promise of reducing GHG emissions. Global warming is mainly because of extra-production of CO_2, CH_4, and N_2O. CH_4 comprises 18% of total GHGs. Cropland management, livestock management, bioenergy, grassland management, manure/bio-solid preparation, and management of lands are the main areas on which we have to focus for reducing the production of these GHGs for minimizing the damage caused by global warming (Smith et al. 2008). To mitigate the global warming consequences, reducing emissions of CH_4 (by using improved resource conservation technologies) and N_2O (by using improved fertilizer application technologies) from agriculture along with fossil fuel by enhancing removal of atmospheric GHGs must be encouraged. Mitigation could be accomplished through intensification (may increase emission of GHGs ha^{-1}) and intensification (may reduce emission of GHGs ha^{-1}) of agriculture but total land requirement may increase slightly.

Different mitigation strategies can be classified into three categories:

1. By reducing gas emissions with practices which ultimately improve fertilizer use efficiency by minimizing their losses and reducing CH_4 emissions by implementing suitable RCTs to mitigate global warming consequences.
2. By enhancing carbon sequestration through increasing land productivity in one or other ways, thereby requiring less land for cultivation, by taking carbon for the development of plant edible portions, by increasing photosynthetic storage of carbon through agroforestry ecosystems, and by reducing CH_4 from the atmosphere by reducing the agricultural lands.
3. Avoiding emissions: Biofuels and biodiesel avoid excessive consumption of fossil fuels as CO_2 (Houghton et al. 1996). Fossil fuel burning, industrial processes, and transport fuel contribute about 29.50%, 20.60%, and 19.20%, respectively (Raupach et al. 2007).

Fossil fuel burning led to an upsurge in the concentration of atmospheric CO_2 at the rate of 1.8 ppm $year^{-1}$, which might reach 550 ppm by the end of this century (IPCC 2007a, b, c). The CO_2 concentration is reported to be peak up to now (IPCC 2007a, b, c). Fossil fuel burning (5.7 Gt) and deforestation (2.3Gt) further contribute to it. Soil organic carbon (SOC) is reduced to almost half over the past four decades due to global warming (Lal 2004). The downcoming of SOC has become a matter of worry, as SOC is the main pillar for improved soil physical, chemical, and biological health which further supports higher land and water productivity in the region. Therefore, carbon must be sequestered by adopting one or other ways for mitigating the global warming consequences.

2.8 Conservation Agriculture for Practicing Climate-Smart Agriculture

Different approaches of conservation agriculture help in adoption of climate-smart agriculture in extensive, mechanized agricultural sequence on erosion-prone, structurally deteriorated soils. Furthermore, climate change led to a number of problems that stood in front of sustainable agriculture (Thomas and Twyman 2005). Different traffic technologies and principles of conservation agriculture further provide improvement in the livelihoods (Robertson et al. 2008; Meena et al. 2016a). Furthermore, the adoption of CA will help in improvement of both soil and environment quality at the ecosystem level (Fig. 2.2).

Within India, CA principles within a particular agricultural system remain logical due to the diverse factors that might be social or economic. Generally, conservation agriculture involves the following principles:

1. Crop rotation: This is a must exercise for changing the soil depth explored for the nutrients as rhizosphere area changes with every crop. Therefore, crop diversification, viz., rice with maize, increases livelihoods of the local farmers.
2. Minimum tillage: Minimum tillage not only reduces the bulk density as in the case of zero tillage but also sequesters higher amounts of C and thereby minimizes emission of GHGs. Furthermore, by improving soil organic carbon status, minimum tillage ultimately improves the soil health (Jat et al. 2009) which finally improves the soil eminence. But to have a significant improvement, a certain set of periods of 3–5 years is required (Bhatt 2015).
3. Mulching: Mulching, viz., placement of the crop residues on the soil surface, improves the soil moisture holding capacity (Bhatt and Khera 2006; Bhatt and Kukal 2017; Kumar et al. 2018a), maintains the soil temperature (Singh et al. 2011a), and finally improves the grain yields (Kukal et al. 2014; Meena et al. 2015b). Basically, crop residues hinder the direct contact of the hot sunrays onto the soil, decrease the vapor pressure gradient, and minimizes the vapor lifting capacity of the wind by minimizing its speed near the soil surface.

It is very important to know the interaction occurring between conservation agriculture techniques and the other resource conservation technologies (RCTs) which certainly increase both land and water productivity (Kirkegaard and Hunt 2010; Kumar et al. 2018b). But C-sequestration potential (Chan et al. 2011), GHG minimum emissions (Maraseni and Cockfield 2011), and higher energy usage (López-Moreno et al. 2012; Meena et al. 2017c) are often assumed for zero-tillage systems. Dealing with these illogicalities will be dominant if CA principles are to be functional wisely to exercise sustainable agriculture. Different possibilities, viz., spreading crop residues onto soil surface, zero tillage, etc., delineate important principles of CA which has the potential to mitigate global warming consequences.

4. Technologies to mitigate the consequences of the global warming: One could adopt the following technologies to meet the objective of having improved land and water productivity.

2.8.1 Agronomic Practices

1. Soil test-based fertilization will certainly reduce overfertilization resulting in lower N_2O emissions which further mitigate the global warming consequences. Therefore, farmers must go for soil test-based fertilization instead of deciding fertilizer dose by having a watch on the neighboring farmers.

2. Fertilization timing: Fertilization as per crop need is very important to avoid losses of N_2O to the atmosphere.
3. Use slow-release fertilizers, viz., neem- or poly-coated urea, which certainly slow down the release of the nutrients, thus increasing their N use efficiency, e.g., greater granule size of urea, diminished nitrification rates, and minimized GHG emissions.

2.8.2 Technology to Improve Nitrogen Use Efficiency

Nitrogen use efficiency management practices, viz., fertilizer granule type, time of application, depth of placement, and their interaction with irrigation timings and rainfall events, affect N_2O emissions. Fertilizer applied affected the production of N_2O. Venterea et al. (2005) observed higher N_2O emissions with urea than those with anhydrous ammonia, while Tenuta and Beauchamp (2003) delineated higher magnitude of total emissions with urea than with ammonium sulfate, with that of calcium ammonium nitrate being higher. Proper fertilizer droppings in the rhizosphere can decrease nitrogen losses which on the long run mitigate the global warming consequences. Furthermore, nitrification and urease inhibitors delay transformation of NH_4 to NO_3 and urea to ammonia to match crop demand. S-Benzylisothiouronium butanoate and S-benzylisothiouronium fluroate increased overall land productivity and increased nitrogen use efficiency (NUE) by 4–5% (Bhatia et al. 2010; Varma et al. 2017a). Cover crops may be used on sloppy lands to reduce N_2O emissions, while storing animal waste anaerobically minimizes N_2O losses out of soil. Losses of N through leaching, volatilization, and denitrification decreased on adoption of irrigation on 2-day intervals instead of continuous irrigation in paddy fields.

2.8.3 Adaptation Technologies

Adaptation is one of the most important aspects to stand and perform in the present time of climate change as otherwise crop plants may not be able to yield as per their potential. The following are the techniques which could really help in the adoption:

1. Crop breeding for development of new heat- and low water-tolerant crop cultivars is a major intervention which helps us to practice climate-smart agriculture in the region. Plant breeding has a great potential to develop new more resistant, heat- and salt-tolerant crop cultivars which adapt to adverse climatic conditions. New cultivars have the potential to withstand the more adverse conditions.
2. Proper crop rotation is the next secret and one of the basic principles of conservation agriculture which enables us to sustain land and water productivity. Different crops growing at one time on a single piece of land, viz., intercropping, holds the promise for sustainability even in the era of global warming.

2.9 Research and Development Need

Development of both low water- and salt-tolerant crop cultivars is the need of the time which also provides us reasonable yields by improving both nitrogen and water use efficiency. Furthermore, there is a need for continuous marking of the different adopted tracks against global warming and breeding new crop cultivars with resistance to new diseases and pests which could be recommended to the farmers for growing under the present era of climate change.

Mitigating global warming consequences with or by adopting one or other more suitable integrated approaches is the main challenge in front of agricultural scientists. New incentives should be there for the farmers practicing climate-smart agriculture and adopting its different principles. New encouraging and supporting policies must be there for better adoption of these resource conservation technologies as many of proposed technologies are site and situation specific, and there is a need to specify them as per conditions.

2.10 Carbon and Water Footprints in the Rice-Wheat System

This concept was introduced about a decade ago. The terminology chosen in both the cases was enthused by ecological footprint (EF), which was introduced in the 1990s (Rees 1992). All foot prints delineates human arrogates use of natural resources of this planet's, in different ways. The ecological footprint delineates the use of bio-productive space in hectares; the carbon footprint measures the emission of gases that contribute to heating the planet in carbon dioxide (CO2) equivalents per unit of time or product; and the water footprint measures the consumption and contamination of freshwater resources in cubic meters per year. All footprints can be related to specific accomplishments, produces, and ingesting designs.

A carbon footprint is defined as the total emission caused by an individual, event, organization, or product, expressed as carbon dioxide equivalent. It is difficult to calculate carbon footprint accurately because of inadequate knowledge and data explaining the complex interactions between processes contributing to or influencing the natural processes of releasing or storing CO2. Hence, Wright, Kemp, and Williams have suggested defining the carbon footprint as a measure of the total amount of carbon dioxide (CO2) and methane (CH4) emissions of a defined population, system, or activity, considering all relevant sources, sinks, and storage within the spatial and temporal boundary of the population, system, or activity of interest (calculated as carbon dioxide equivalent using the relevant 100-year global warming potential) (Pfister et al. 2017; Yadav et al. 2018a).

Carbon footprint is more specific than other footprints, since it measures direct emissions of gases that cause climate change in the atmosphere. It is extensively acknowledged and used by the public and describes GHG emission measurement from the narrowest to the widest sense. There are several calculation methods and approaches for carbon footprint accounting that are being used. Carbon trade in developed countries is supported by research in advances in carbon footprint (Hillier et al. 2009). For instance, consumers are guided regarding the different products used by them and their contribution to GHG emissions, thereby an attempt being made to guide them for using low-gas-producing gadgets (Burney et al. 2010; Kakraliya et al. 2018). With the increase in carbon emissions, there is a need for socioeconomic transformation and development of a carbon market and associated management techniques (Röös and Tjärnemo 2011; Zhang and Zhang 2016; Meena et al. 2018a), but insufficient research related to quantifying carbon footprints to support such a management system is making carbon trading difficult.

Greenhouse gas emissions and the relative forcing on global warming have inspired the quantification of the carbon footprint of the economy. It is determined as the GHG emissions in carbon equivalents (CEs) caused by the production of a certain product (Wright et al. 2011). Carbon footprint is meant to denote a degree of the exclusive total amount of carbon dioxide emission that is directly and indirectly caused by anthropogenic activity (Dubey and Lal 2009). For example, the UK Greenhouse Gas Inventory estimates the proportion of the nation's overall carbon footprint due to agriculture to be around 8%, out of which 75% can be contributed by fertilizer use. It is difficult to pinpoint the carbon footprint of a specific activity, but recently thorough studies into the contribution of specific agricultural events during crop production to the global footprint are being conducted (Wiedmann and Minx 2008; Yadav et al. 2017a).

The carbon equilibrium can be an indicator of agricultural fabrication. The agriculture sector has been widely recognized as a significant source of GHGs to the global total GHG emissions (54% of methane and 58% of nitrous oxide produced via agricultural activities which further contribute to global warming). Methane is generally produced by microbial decomposition of organic matter under submerged conditions during rice season. Furthermore, denitrification is responsible for the production of the N2O gas which has 265 times global warming potential (GWP) than CH4. Uninterrupted submergence, advanced organic C content, and use of organic fertilizer in puddled soils improve methane discharge, while burning of crop residues contributes to the global methane and nitrous oxide emissions.

A substantial amount of methane emission has been attributed to enteric fermentation in ruminants. Moreover, nitrogenous nourishments are the source of N2O in inseminated soils, whereas the indigenous N can contribute to its release in unfertilized soil. It has been observed that N2O emission increases following irrigation and precipitation. Carbon dioxide also occurs from agricultural activities, viz., soil organization practices such as tillage that can trigger carbon dioxide emission through biological decomposition of soil organic matter. Fuel use for various agricultural processes and burning of crop remains are the other sources of carbon dioxide productions. Fertilizers and manures are sources of off-site CO2.

The net GHG emission in 2007 in India was 1727.7 million tons (Mt) of CO2 eq. The main foundation was the energy sector, contributing 57.8% to the total GHGs, followed by industrial (21.7%), agricultural (17.6%), and leftover (3.0%) sectors. In the agricultural subdivision with a total production of 334.4 Mt CO2 eq., the chief foundations were enteric fermentation (63.4%), rice agronomy (20.9%), farming soils (13.0%), compost running (2.4%), and on-field burning of crop residues

(2.0%). Thus, the crop manufacture sector (rice cultivation, soils, and field burning of crop residues) underwrote 35.9% of the total emanations from farming (Leach et al. 2012).

Carbon accounting is the assessment of carbon footprint of an individual, a nation, or an organization. Population, financial production, and vigor and carbon strength of the economy are the main influences on carbon footprints. When an organization or an individual aims at reducing its carbon footprint, they target and manage these factors. Production activities require a lot of energy and leave a large carbon print; hence, by decreasing the amount of energy needed for production, the carbon footprint can be decreased most effectively. These are identified as carbon counteracting, a response to carbon dioxide emanations with a corresponding reduction of carbon dioxide in the troposphere (Corbett 2008). Alternative projects such as solar/wind energy (renewable sources of energy), reforestation, etc. can also reduce carbon footprints. Once the size of the carbon footprint is known, appropriate strategies can be devised to reduce it.

Greenhouse gas production caused by the construction of agricultural produce via the use of farm equipment; elements such as herbicides, insecticides, and fungicides; and fertilizer for crop protection and nutrition is referred to as carbon footprint in agriculture. So it is important to identify the carbon footprint of a crop for making agriculture sustainable (IPCC 2006; Singh 2016). Carbon secretion or carbon penalties induced by production practices in a growing season may be termed as a carbon footprint of a crop (West and Marland 2002; Smith et al. 2008; Smith 2013; Meena and Yadav 2014).). The carbon footprint (CF) is assessed by taking into account the total GHG emission in carbon equivalent (CE) through material added and from a mechanical operation performed in a single cycle of crop production (Hillier et al. 2009).

Rice is the principal nourishment for over 60% of the biosphere's inhabitants. About 50% of the anthropogenic emissions of methane are attributed to agricultural activities, out of which 10% is contributed by rice cultivation (Scheehle and Kruger 2006; Dadhich and Meena 2014). In continuous flooding conditions, carbon emission in rice varies from 21.96 to 60.96 Tg C year^{-1} due to variation in urea doses (Pathak et al. 2005). The Intergovernmental Panel on Climate Change estimates that the annual global emanation rate of methane from paddy fields is to average at 60 Tg year^{-1}, with a range of 20–100 Tg year^{-1} (Blengini and Busto 2009) which is nearly 5–20% of the total CH4 emissions from anthropogenic sources. In China, carbon concentration fluctuated from 0.64 t CE ha^{-1} year^{-1} in 1993 to 0.92 t CE ha^{-1} year^{-1} in 2007 in terms of cultivated lands and from 0.14 t CE t^{-1} in 1993 to 0.11 t CE t^{-1} in 2007 in terms of whole production (Bockel 2009). Crop residue burning is a potential source of emission of CO2, CH4, and N2O, plus pollutants such as carbon monoxide (CO), particulate matter (PM), and toxic polycyclic aromatic hydrocarbons (PAHs) (Cheng et al. 2011; Verma et al. 2015c). In Italy, the estimated carbon footprint of rice (sowing to farm gate) was 2.90 kg CO2-e kg^{-1} yield. A study in Japan on over 100 producers which examined five life cycle stages, raw material production, rice polishing, retailing, rice cooking, and waste treatment, showed that the carbon footprint of rice was 7.7 kg^{-6} CO2eq 4 kg^{-1}-1 of polished rice.

Wheat carbon footprint, like rice, also is contingent on grain yield and total GHG releases related to crop construction. Rajaniemi et al. (2011) analyzed greenhouse gas (GHG) emissions from wheat production in Finland. The GHG emissions were analyzed in a conventional production chain, direct drilling chain, and reduced tillage chain. The GHG emissions for wheat were 590 g CO2 eq kg^{-1} (Lemieux et al. 2004). In Canada, the carbon footprint for spring wheat was estimated to be 0.357–0.140 and for durum wheat 0.383–0.533 kg CO2-e kg^{-1} yield (Rajaniemi et al. 2011). A report says that in the case of wheat, CF for conventional tillage is 262 kg CO2 ha^{-1} where grain yield average is 2287 kg ha^{-1} (Gan et al. 2011). Fix and Tynan (2011) delineated that GHG emissions for wheat were 720 g kg^{-1}.

Water footprints were presented in the field of water possessions organization in 2002, as a tool to measure water use in relation to ingesting patterns and indicates the water required to sustain a population. The water footprint of a nation is defined as the total volume of freshwater that is used to produce the goods and services consumed by the people of the nation. Since not all goods consumed in one particular country are produced in that country, the water footprint consists of two parts: the use of domestic water resources and the use of water outside the borders of the country. The water footprint is carefully linked to the simulated water notion. The volume of water required to produce a commodity or service is called virtual water. When assessing the water footprint of a nation, it is essential to quantify the flows of virtual water leaving and entering the country. If one takes the use of domestic water resources as a starting point for the assessment of a nation's water footprint, one should subtract the virtual water flows that leave the country and add the virtual water flows that enter the country.

The total volume of water used worldwide for crop fabrication is 6390 Gm^3 year^{-1} at field level. Rice has the principal portion in the total volume of water used for worldwide crop production (Wanhalinna 2010; Meena et al. 2016b). It chomps about 1359 Gm3 year^{-1}, which is about 21% of the total volume of water used for crop production at field level (Table 2.2). The subsequent largest water consumer is wheat (12%). The input of some foremost crops to the universal water footmark in so far as related to food feeding is presented below.

Comparatively on an average, the water productivity of rice is much lower than that of wheat because of required anaerobic conditions (Hoekstra and Chapagain 2006).

2.11 Integrated Approach to Enhance Water/Land Productivity Under the Current Scenario

Rice-wheat cropping sequences prove to be labor, energy, water, and capital intensive which further caused structural deterioration of the soil and decline in underground water (Bhatt et al. 2016; Bhatt and Kukal 2017; Dhakal et al. 2016). As per one estimate, a significant area is already under RWCS prevailing in South Asia, out of which around 85% falls in the IGP (Timsina and Connor 2001; Ladha et al. 2003; Varma et al. 2017b). The output and sustainability of rice-wheat-based systems are in question because of the declining underground water table, rising micronutrient

Table 2.2 Involvement of some major crops in the worldwide water footmark (Wanhalinna 2010)

Crop	Contribution (%)
Rice/paddy	21
Wheat	12
Maize	9
Soybean	4
Sugarcane	3
Cotton	3
Barley	3
Sorghum	3
Coconut	2
Millet	2
Coffee	2
Oil palm	2
Groundnut	2
Cassava	2
Rubber	1
Cocoa	1
Potato	1
Minor crops	26

deficiencies, increasing scarcity of resources especially water and labor, emerging energy crisis, and rising fuel prices (Bhatt 2015). Global water scarcity analysis has shown that up to two-thirds of the world population will be affected by water scarcity over the next several decades (Wallace and Gregory 2002). The fall in water table particularly in central Punjab has been reported to increase from 0.2 m year^{-1} during 1973–2001 to about 1.0 m year^{-1} during 2000–2006. As per Humphreys et al. (2010), majority of the blocks in Punjab are being overexploited for pumping out groundwater. The lowering of the groundwater table in the state has been resulting in an increase in the energy requirement and tube well infrastructure cost and deteriorating groundwater quality (Hira 2009). Moreover, coarse- and medium-textured soils when puddled cause subsurface compaction (Sur et al. 1981; Kukal and Aggarwal 2003a), which causes yellowness in wheat leaves due to aeration stress (Kukal and Aggarwal 2003b). The high bulk density layer at six to seven inches appeared as a consequence of repeated puddling by closing earth pores for rice which restricts the wheat root growth during rabi season (Aggarwal et al. 1995; Kukal and Aggarwal 2003b; Meena et al. 2015a).

In India, per head water availability will decrease to 1000 m^3 up to 2025 if necessary steps will not be implemented (UNEP 2008). Water availability decreased as the region's population increased significantly over the last half decade (Ali et al. 2012). Climate change impacts cereal production in one or other ways, i.e., either through stress or through weather irregularities (Porter et al. 2014). Summer months reported with excess, while water shortfalls were observed during winter seasons; thereby, adoption of an integrated approach is a must for sustainable agriculture in South Asia (Ali et al. 2012).

Integration of different approaches which could indirectly—viz., soil test-based fertilization, integrated nutrient management, leaf color chart, and slow-release fertilizers (neem-coated urea or poly-coated urea)—or directly, viz., laser leveling, short- or medium-duration crop cultivars, transplantation/sowing time, 2-day intermittent irrigation, soil matric potential-based irrigation, permanent beds, rice without puddling (DSR), transplanting of rice with machines, etc., enhance the so declined land and water productivity in the region is an approach dependent upon the divergent soil and climatic conditions (Bhatt and Kukal 2014; Verma et al. 2015b). Furthermore, to mitigate the global warming consequences, a properly integrated approach by using two or more approaches along with new genetically modified water-stress cultivars in all is very important to improve the declining terrestrial as well as aquatic efficiency under the scenario of global warming (Bhatt and Kukal 2014). Increased soil temperatures because of global warming will cause water stress which is further reported to affect different yield and quality parameters in cereals and grass crops, viz., sugarcane (Sanghera et al. 2018; Sanghera and Bhatt 2018). Moreover, studying the residual effect of adopted resource conservation technologies during the intervening period on the soil moisture dynamics is a must (Bhatt and Singh 2018). Soil management practices, viz., tillage, certainly affect the livelihoods of the farmers (Bhatt and Khera 2006; Bhatt and Kukal 2017; Meena et al. 2017a). It is very well clear up to now from the different studies carried out across the globe that total evapotranspiration losses remain almost the same. If we decrease evaporation somehow with some measure, viz., mulching or short-duration crop cultivars, then certainly a higher fraction of the ET water will partition toward the transpiration (T) component, finally improving the inflow of the nutrients along with water, which further improves the declining water and land productivity. Therefore, there is a need for proper selection, integration, and recommendation of a full package (depending upon the socioeconomic status of local farmers); and follow-up plan will certainly help the farmers to practice climate-smart agriculture in the region. But again, one thing must be remembered: the performance of these RCTs is site specific, and one should be very careful while selecting them. Hereby, we are going to discuss them one by one briefly.

2.11.1 RCTs Cutting Off Evaporation Losses and Their Effect on Land and Water Productivity

2.11.1.1 Short-Duration Crop Cultivars

The shorter the stay of a crop in the field, the lesser the evaporation is, and thus the lesser the total number of irrigations which finally results in higher water productivity. Pusa-44 takes about 160 days and consumes significantly higher irrigation water with comparatively lower yields compared to PR-126 and PR-127 which take about 123 and 137 days, respectively, which further saves about 15–20% of irrigation water along with a cutdown two sprays of insecticides (PAU 2018). Therefore, the farmers of the regions suffering from shortage or scarcity of water, viz., central Punjab, must cultivate short- or medium-duration crop cultivars recommended by state agricultural universities for improving both land and water productivity.

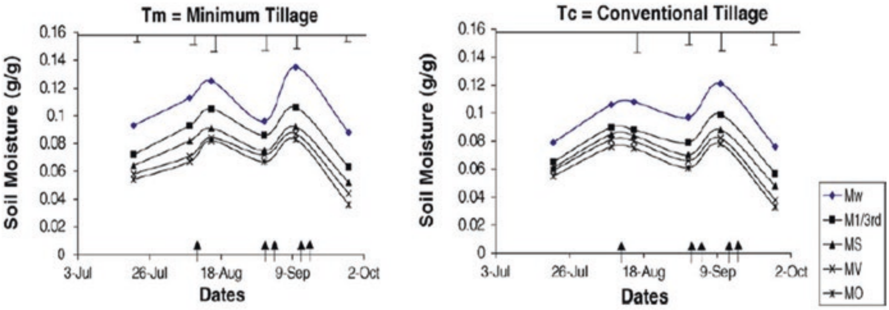

Fig. 2.3 Soil moisture content of surface soil vis-a-vis tillage and mulch application (Bhatt and Khera 2006)

2.11.1.2 Mulching

Mulching is a practice by which the so remained crop residues spread over the bare land which is reported to improve overall livelihoods by avoiding contact of hot radiations, regulating the soil temperature regimes, decreasing vapor pressure difference within soil and ambient air, decreasing lifting capacity of the air, and suppressing weeds (Fig. 2.3) (Bhatt and Khera 2006; Bhatt et al. 2004; Yadav et al. 2017b). Furthermore, Jalota et al. (2007) delineated 7–40 cm of irrigation water savings with mulching; and the benefits from mulch are contingent upon seasonal rainfall, irrigation regime, soil consistency, and kind of mulching material. Mulching reduced soil evaporation component by 15.8 cm in maize and 20 cm in both cotton and sugarcane (Jalota and Arora 2002).

However, improvement in land and water productivity decreased drastically if mulch load was removed which even affected the performance of the resource conservation technologies (Bhatt and Kukal 2017). Bhatt and Kukal (2015a, b) reported that removing mulch loads during intervening periods causes increased soil temperature, lesser volumetric content, and finally higher evaporation losses in the rice-wheat cropping sequence depicting the importance of the mulch in overall improvement of the sustainability of this sequence in the region.

2.11.1.3 Zero Tillage

As far as dealing with crop residues is concerned, almost every option has a limitation. Burning residues in the field then causes air pollution and allows the fixed carbon to go back in air which further causes global warming (Bhatt 2016, 2017; Bhatt and Singh 2017; Ram and Meena 2014). Another option is the incorporation of the residues back into the soil, but this option causes N immobilization and causes yield loss in the next crop. So finally, what should be done? The answer to this very question is Happy Seeder which directly drills wheat seeds in standing rice stubbles. Furthermore, there is no need for pre-sowing irrigation which finally causes around 30% savings in irrigation water (Singh et al. 2008). Experiments carried out at different agroclimatic regions delineated that in wheat, there was more pronounced effect on water conservation observed in dry periods with reduced and no-tillage systems (Rahman et al. 2005; Verhulst et al. 2011). Rice stubble mulch augmented mean wheat grain yield by 17.1%, lessened crop water uses by 3–5%, and enhanced WUE by 38.3% associated with no mulch (Chakraborty et al. 2010; Meena et al. 2018b). Probably due to greater retaining of soil wetness in the more profound layers with mulch, roots grow 25% higher compared to those with no mulch in lower layers (>0.15 m). Happy Seeder allowed sowing of wheat seeds in the standing paddy stubbles without removing rice stubbles outside the field along with sharing the benefits of mulching which decrease the evaporation losses and decrease the amount of water used per irrigation and partition higher fraction of evaporation component to transpiration which ultimately improves land and water productivity in the region.

But at some sites, zero-tillage plots are reported to be having significantly higher weed population. The reason claimed by different scientists is remaining of weeds on the soil surface which further enjoyed the higher availability of moisture and nutrients while under conventional tillage and weed seed placed deeper in the soil depending upon the tilling depth of the instrument used. At deeper depths, both moisture and nutrient availability is cut down which significantly affects their germination and, thus, finally cuts down weed pressure significantly higher than that of zero-tillage plants (Bhatt and Kukal 2017; Bhatt 2015; Singh et al. 2015a, b).

2.11.1.4 Date of Transplanting

Date of transplanting is very crucial for uplifting livelihoods of poor farmers in the rice-wheat cropping sequence as early transplanted crop has highest evapotranspiration losses and lower land and water productivities (Table 2.3), the reason being that in May air is dried and has higher water evaporated by it; thus, we have to apply frequent irrigations to meet irrigation requirements of the plants. With transplanting after June 20, monsoon arrives in July–August, which increases the humidity in air and decreases its vapor lifting capacity; and finally duration in between two irrigations increases and lowers the total number of irrigations, which finally results in higher water productivity. The water productivity is reported to be 17% higher in June 25 transplanted rice than May 25 transplanted rice. Jalota et al. (2009) using the CropSyst model estimated a significant improvement in water productivity by adjusting transplanting date and crop cultivars.

Table 2.3 Effect of transplanting date and variety on yield and water requirements of rice (Jalota et al. 2009)

Transplanting date	Irrigation water (mm)	Grain yield (t ha^{-1})	Irrigation water (mm)	Grain yield (t ha^{-1})
	PR-118 (155–160 days)		RH-257 (110–120 days)	
May 25	2530	7.5	2350	6.8
June 10	2420	6.6	2310	7.3
June 25	2270	7.1	2120	7.5
Mean	2407	7.1	2260	7.2

2.11.1.5 Crop Diversification

Crop diversification plays a pivotal role in decreasing the amount of irrigation water required, and it was revealed that (Jalota and Arora 2002; Arora et al. 2008; Dadhich et al. 2015) particularly diversion from rice helped to increase water productivity for the system as a whole. Evapotranspiration losses decrease if the system is diversified from rice-wheat rotation to cotton-wheat or to maize-wheat rotation as cotton and maize have lesser water requirements (Table 2.4).

Wetland puddle rice must be replaced with other alternative crops to lower ET requirements. The photosynthesis and crop-specific seed composition are two most important factors affecting land productivity (Ali et al. 2012). The exchange between leaf photosynthesis and water loss is comparatively higher in C_4 crops. By substituting rice with maize in the rice-wheat system, the irrigation water is reported to be lower, but productivity of the rice-wheat system is still in question (Gathala et al. 2014; Meena et al. 2017b). The WP_I of rice (5–5.6 kg m^{-3} based on rice corresponding yield) was 8–22 times lower than that of maize. The maize-wheat cropping system had 126–160% higher irrigation water productivity than that of the rice-wheat cropping system.

2.11.2 RCTs Cutting Off Drainage Losses and Their Effect on Land and Water Productivity

2.11.2.1 Direct Seeded Rice

For reducing the irrigation water amounts (in puddling operations) and for improving the degraded soil structure (caused by puddling), direct seeded rice (DSR) is a way out as it neither involves the puddling operations nor involves the standing irrigation water for 15 days (as in AWD and in tensiometers). This RCT sows directly rice seeds into the soil using seed cum fertilizer drill. However, the land productivity often is somewhat lower due to severe iron deficiency; much more weed pressure etc. as it particularly more truely in the zero till DSR plots. Furthermore, it is very important to consider the rice-wheat system as a whole including intervening periods. Bhatt (2015) observed significantly higher irrigation water productivity in conventional tillage DSR than zero-tillage DSR.

In DSR, it was observed that aerobic rice cultivars responded well than the lowland cultivars in terms of grain yield under water-stressed conditions, viz., water-deficient areas; however, under submerged conditions, the lowland cultivars had an edge over the aerobic cultivars (Bouman et al. 2007). Direct seeded cultivars have a lower yield potential than the flooded cultivars but with 50% less consumption of water. Thus, they could be very well cultivated in a region facing scarcity of water and having heavy-textured soils as this technology proves to be a failure in the light-textured soils (Bhatt and Kukal 2015a, b, c, d; Kumar et al. 2017a).

2.11.2.2 Laser Leveling

Among various RCTs advocated for the region for improving land and water productivity, laser leveling is widely accepted and adopted because of the fact that laser

Table 2.4 Diversification for improving water productivity (Jalota and Arora 2002; Arora et al. 2008)

Cropping systems	ET (mm)	E_b (mm)	Land productivity (t ha^{-1})		Wheat corresponding yield (t ha^{-1})	Water productivities (kg m^{-3}) based on	
			C_1	C_2		ET	NWL
Rice-wheat	1030	210	6.0	4.5	9.7	0.94	0.78
Cotton-wheat	980	901	2.0	3.5	8.6	0.88	0.80
Maize-wheat	860	220	3.5	4.5	7.2	0.84	0.67

leveling levels all the dukes and dikes and causes uniform distribution of water and causes irrigation on a large area within a shorter period of time. Around 25–30% of irrigation water could be saved with laser leveling without affecting crop yields (Bhatt and Sharma 2010). Furthermore, Jat et al. (2009) have well documented the crop yield augmentation coupled with improved irrigation water productivity with precision land leveling.

2.11.2.3 Permanent Beds

Permanent beds are recommended for increasing the declining land and water productivity. Jat et al. (2005) observed comparatively higher irrigation water productivity (kg grain m^{-3} water) under permananet beds than in CT (42%) and ZT (35% higher), respectively; but Kukal et al. (2009) have reported no savings in amount of irrigation water under PTR and transplanted rice on permanent raised beds in a sandy loam soil, because of higher cracking of loam in permanent beds when a full-furrow depth of irrigation was applied; but on the contrary, higher water use efficiency (WUE) was observed in bed-planted crops (Brar et al. 2011; Sihag et al. 2015) although with time, the irrigation water productivity on permanent beds decreased as slopes of side beds were compacted due to tractor tire pressure during repeated reshaping (Kukal et al. 2008). But Kukal et al. (2008) further provide evidence that these beds were quite effective initially but year after year due to reshaping operation the side slope of beds got compacted resulting in higher bulk density. Moreover, the surface area of these beds was about 25% higher, resulting in higher absorption of radiant energy which resulted in higher evaporation losses and more water needs; and finally aged beds had lower water productivity.

2.11.2.4 Soil Matric Potential-Based Irrigation

It is the main driving force as water moves from higher energy level to the lower energy level (Bhatt et al. 2014). Tensiometer measures the soil matric potential, thus a quite effective technique to decide when to irrigate a crop based on the soil suction behavior (Fig. 2.4). Kukal et al. (2005) and Bhatt and Sharma (2010) reported that soil matric tension-based irrigation scheduling helps in significant savings of irrigation water with almost similar/higher yields, thus helping in increasing water productivity in the region as it dictates the farmers as when to irrigate. In the absence of the mulch load, tensiometer depicted higher SMP readings than that of the mulched plots indicating higher evaporation losses (Bhatt and Kukal 2015a, b).

2.12 Conclusions

The rice-wheat cropping sequence in South Asia has taken a toll on natural resources, air, water, and soil. Several resource conservation technologies, viz., zero tillage in wheat and direct seeding and mechanical transplanting of rice under different tillage conditions, being advocated in the region, have been studied under isolated conditions for individual crops and are shown to be resource-conserving techniques. Furthermore, changes in rainfall patterns, increasing temperatures, and frequency of

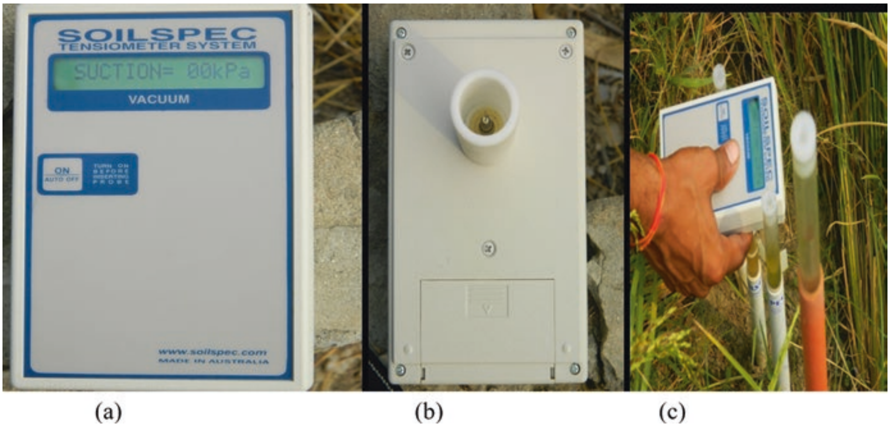

Fig. 2.4 Soil spec front view (**a**), rear view (**b**), and in action measuring soil water tension (**c**)

extreme weather actions, viz., droughts, floods, etc., are expected to slow down the progress toward sustainable agriculture. These consequences of climate change are already having serious impacts on crop yields, especially for the rainfed regions. Therefore, an integrated approach is the requirement of the time (keeping in mind the socioeconomic conditions of the local farmers) to improve the ever-decreasing livelihoods of South Asian farmers in the current period of climate change. CSA is an answer to all these urgencies whose principles help us to fulfill all demands of food in the era of ever-decreasing land resources and when the whole world is facing abrupt change in the weather parameters. CSA also reduces soil degradation by increasing soil organic matter and by reducing soil organic carbon losses through oxidation by advocating the concept of zero tillage and thus increasing resilience to climate change impacts. Scientists must have to evaluate sound scientific resource conservation technologies which have the potential to minimize the emission of CO2, CH4, and N2O gases in the atmosphere. Furthermore, new agricultural programs/schemes/plans provide a good opportunity for CSA practices either by providing some incentives or by creating awareness among the local farmers. One must consider the following points to formulate the new policies:

(a) Enabling policymakers, institutions, makers of legal frameworks, financers, and the government to act for practicing CSA in a better way.
(b) Climate change and opportunity must be studied even at school level for identifying the emergency to apply CSA.
(c) Climate projections and trends must be delineated at regular intervals.
(d) For mainstreaming and scaling up CSA, there is a need to map CSA practices along with capacity building, changing mind-sets, and enhancing regional collaboration.

Therefore, there is a need to identify the seriousness of the present situation by sharing knowledge; facilitating collaborations; setting goals of both improved land

and water productivity; raising awareness among all who could contribute, viz., students, farmers, extension workers, and policymakers; knowledge upgrade as well as technical support, and then finally execution at the farm.

There is a need to check the performance of a particular set of CSA technologies after a certain period of time, thereafter making certain effective changes wherever required after obtaining the consent of the local farmers. Furthermore, adoption of CSA practices largely depends on updating the extension worker inherent knowledge, formulating farmer-friendly political action plans, proper understanding between farmers-extension workers and government bodies, and proper storage facilities for proper storage of surplus grains. Farmers adopting CSA practices thereby emitting lower greenhouse gases will be rewarded, and this practice will certainly encourage the others. Proper crop insurance must be there for maintaining livelihoods even in case of certain uncertainties, viz., floods, droughts, etc. Small farmers generally hesitate to adopt CSA practices generally because of financially limited resources and unawareness toward a new approach as mostly they want to walk on the road of their forefathers without deflecting from it. For financial limitations, governments, different NGOs, NABARD, and other cooperative banks must propose good schemes for CSA farmers, while for improving awareness, national education and research systems should be strengthened.

2.13 Future Strategies

For the upcoming CSA programs to be effective, the following actions must be planned for overall improving the declining land and water productivity in the region:

- By adopting a proper concerted mechanism, improve acceptance of climate change in agriculture by mapping climate change effects and trying to incorporate them in seasonal climate outlooks.
- By involving local people of the area by creating awareness on the influences of global warming on agriculture and its associated sectors, viz., poultry, fishery, dairy, etc., frame different integrated packages for texturally divergent soils.
- Try to frame some common SWOT analysis for countries affected by climate change so that they could develop their own mechanisms to come out from this challenge.
- Appropriate regional platforms either at village, regional, national, or even international level will be established for having healthy interactions between grassroots stakeholders, viz., farmers, scientists, and policymakers.
- The CSA concept will be incorporated in all national reports and communication documents.
- Different committees at state or national level well supported by the policymaking body of the government will be constituted for effective implementation of the CSA programs. Furthermore, more funds will be diverted to CSA activities by the government in different CSA programs.

- New farming techniques, viz., vertical farming, more particularly for the urban areas, are impending for achieving self-sufficiency in food production to meet present food demands.
- Delineation of advocated advanced resource conservation technologies and their interactive effect on declining water and land productivity on a regional scale (using different models joined with environmental information system and remote sensing technique) is a must, which provides us an integrated approach suitable for a particular soil texture and agroclimate.

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Soil Erosion and Management Strategies

3

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Abstract

Rising population and decreasing cultivable land pose a great challenge to modern agriculture. The agricultural production has to be balanced with the ever-increasing population to meet the demands of food supply. These changes have led to intensification of agriculture resulting into conversion of natural vegetation areas to agricultural land. This continued overexploitation of land resources in combination with climatic factors results in removal of the top fertile layer of soil. On the global scale, the period of the earliest significant change in land use corresponds to a first wave of the soil erosion. The areas with human intervention have high rate of soil erosion of 2.92 tha^{-1} year^{-1}. In order to strike a balance between agricultural output and conservation, soil erosion control becomes very essential component. The control and prevention of soil erosion necessitate the development of an integral soil erosion control system with the incorporating methods based on the engineering, agricultural cultivation technology, law enforcement, biological methods, land planning, and management. Soil conservation structures along with advanced soil loss models would be prerequisite toward land management. This chapter addresses the dynamics of erosion and agricultural sustainability through different soil management strategies, which poses challenges similar to those of quantification of future changes in climate or agricultural systems. The chapter is focused on the analyzing and quantifying the effects of changes in land use and management of the eroded soils in the agriculture.

Keywords

Agronomic soil management · Engineering soil management · Soil erosion · Water erosion · Wind erosion

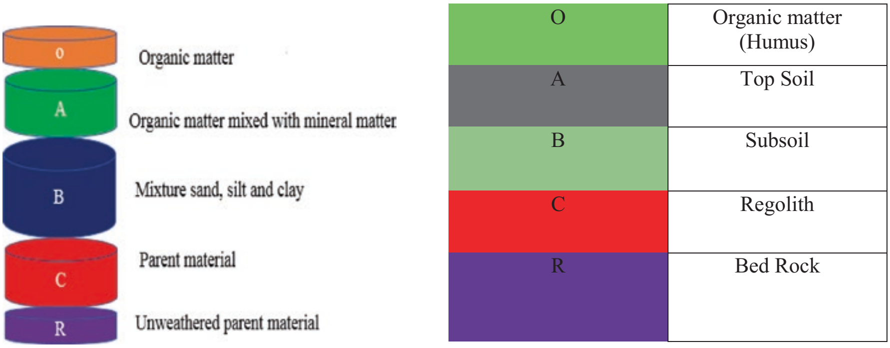
Abbreviations

C	Carbon
cc, cm^3	Cubic centimeter
EI	Rainfall erosivity
FYP	Five-year plan
lps	Liter per second
MUSLE	Modified Universal Soil Loss
RUSLE	Revised Universal Soil Loss Equation

SOM	Soil organic matter
T	Ton
USLE	Universal Soil Loss Equation

3.1 Introduction

Soil can be defined as the organic and inorganic material on the earth's surface resulting from the interaction between atmospheric agents and biological activity in the original material or in the underlying hard rock. Soil provides a physical medium for plant growth. Since the soil supplies nutrients, water, air, and anchoring and is compatible with life on earth, it can be called Infinite Life Soul (SOIL). Among different soil types, alluvial soils form the most important and largest group of soil covering 45.6% of the total land area of India. The type of soil has a significant effect on the hydrological response of a watershed, and therefore, detailed information on soil characteristics is required for hydrological analysis (Beven and Wood 1983; Luxmoore and Sharma 1980; Mirus 2015; Ashoka et al. 2017). The temporal and spatial variations in soil geomorphological and hydrological processes are an integral part of land use types. Both the processes influence pedogenesis and affect the distribution of water, sediments, and organic materials in soil (Young and Hammer 2000; Brunner et al. 2004; Kakraliya et al. 2018). Land use can affect the chemical, physical, and biological properties of the soil due to various anthropogenic activities, such as soil tillage, trampling of livestock, harvesting, sowing, fertilizer application, overirrigation, etc. On the other hand, land use could evolve or disappear in response to regional deviations in soil properties, climate, population density, economic opportunities, cultural practices, and socioeconomic factors (Getahun et al. 2014). Land use is a crucial factor influencing ecological restoration and soil quality in ecologically degraded areas (Hu et al. 2010). Differences in human activity and vegetation have a major influence on changes in biological properties and support the soil structure. The types of biomass and waste influence soil organic matter (SOM), soil nutrients, and microbial biomass. Field observations of the Loess and the red-clay mountain areas in China show that, if done correctly, the restoration of vegetation leads to an increase of nutrients and soil microbes (Zhang et al. 2010; Yadav et al. 2018b). Restoration of vegetation increases the accumulation of nutrients in the plant soil and improves the populations and activities of the microbes in the soil. Climate and human management significantly influence vegetation growth, litter decomposition, and soil nutrient accumulation and microbial activity. Furthermore, different scientists have different opinions about the soil as a whole. Dokuchaev (1900), a Russian scientist and father of soil science, describes the soil as a natural body composed of minerals and organic components, which has a definite genesis and its own distinct nature. Likewise, Joffe (1936) states that "soil is a natural body of minerals and organic constituents generally differentiated into horizons, non-consolidated variable depth that differs between them and the original material underlying morphology, physical composition, chemical and biological



O	Organic matter (Humus)
A	Top Soil
B	Subsoil
C	Regolith
R	Bed Rock

Fig. 3.1 Soil profile describing composition of the different layers of soil

Table 3.1 Soil composition volume basis

Soil component	Contribution (%)
Mineral matter	45
Organic matter	5
Soil water	20–30
Soil air	20–30

composition." The depth of the earth's soil is not uniform everywhere and varies from place to place. It may extend to tens of meters in certain places, whereas in some places, it may be absent altogether. The soil profile can be very diverse and intricate even though it might seem insignificant while comparing with the entire depth of the core of the earth. Five master horizons of varying thickness form the soil profile. Figure 3.1 describes the multitude layers that usually exist in a soil profile. The organic matter (humus) layer is present only in highly fertile soil and is formed by decomposition of organic matter. It is usually found in forests and is usually absent in arable lands. The A horizon also referred to as topsoil is a bio-mantle where most of the biological activity occurs. The B horizon is also referred to as subsoil and consists of different layers of minerals including clay, organic material, iron oxides, and other mineral layers. The C horizon also known as regolith constitutes large chunks of unweathered rock. The R horizon consists of continuous unbroken layer and is quite similar to the bedrock.

The soil is composed of four basic components which include minerals, organic matter, water, and air. The approximate percentage of each component in the soil is given in Table 3.1.

The different properties of the soil such as texture, structure, and color have a profound influence on the soil that behaves like a porous medium. The main influence of these is on the permeability of soil that generally decreases with the decrease in particle size. The soil air that is contained between the individual particles helps in the oxidation process which converts some of the organic material into nitrogen that is readily available to the plants. Soils can treat and maintain a significant amount of water. The ability of the soil to retain water is strictly related to the size of the particles. The water molecules adhere more firmly to the finer particles of a clayey soil than to the coarser particles of a sandy soil. The maximum amount of water that a soil can contain is known as field capacity.

Soil pH is an important measure because the acidity or alkalinity of the soil determines the ease with which plants can absorb nutrients from it. Acidity is prevalent in the regions of heavy rainfall. High rainfall hits appreciable quantities of interchangeable bases from the surface layers of the soils, so as the exchange complex is controlled by hydrogen (H^+) ions. That's why acid soils are widely found in wetlands and greatly influence the plant growth. The soil acidity is the main limitation in the crop production all over the world. Pagani and Mallarino (2012) have described that soil acidity affects many chemical and biological reactions that control the availability of plant nutrients and the toxicity of some elements. Acid soils are seen in vast areas both in the tropics and in the temperate regions. Acidity of the soil affects approximately 3.95 billion hectares worldwide. This is nearly about 30% of the world's ice-free land area. About 16.7% of Africa, 6.1% of Australia, New Zealand, 9.9% of Europe, 26.4% of Asia, and 40.9% of America has acid soils (Von Uexkull and Mutert 1995). They cover a significant part of at least 48 developing countries located mainly in tropical areas, being more frequent in oxisols and ultisols in South America and in oxisols in Africa (Narro et al. 2001). Alkaline soils, which are still a problem, occur when there is a relatively high degree of saturation of the base. Salts such as calcium carbonates, magnesium, and sodium also give a preponderance of OH^- ions above the H^+ ions in the soil solution. When strong base salts such as sodium carbonate enter the soil solution and hydrolyze, they give rise to alkalinity. Saline soils have a number of unfavorable effects on plants that result in decreased growth and yield, including ionic toxicity and nutritional imbalance (Ashraf 2004; Munns and Tester 2008; Meena and Meena 2017). To improve the emergence of crops and the establishment of stands, leaching, mulching, and other specific cultivation practices have been applied in the fields affected by salt (Dong et al. 2009; Bezborodov et al. 2010; Kumar et al. 2018b). Hence, effective techniques for the management of alkalinity and salinity must be developed to address these challenges.

3.2 Factors Responsible for Soil Formation

Soil formation is the combined effect of physical, chemical, biological, and anthropic processes in the ground parent material. As a difficult natural process (Vladychenskiy 2009), the soil formation is influenced by five factors that form the soil (Figs. 3.2 and 3.3): climate, topography, original materials, organisms, and time (Jenny 1941; Dokuchaev 1948). Defining soil formation as a constant process helps to comprehend how they have developed soil and landscapes and how they will be influenced by climate change. Attempts to describe soil production had a varying success.

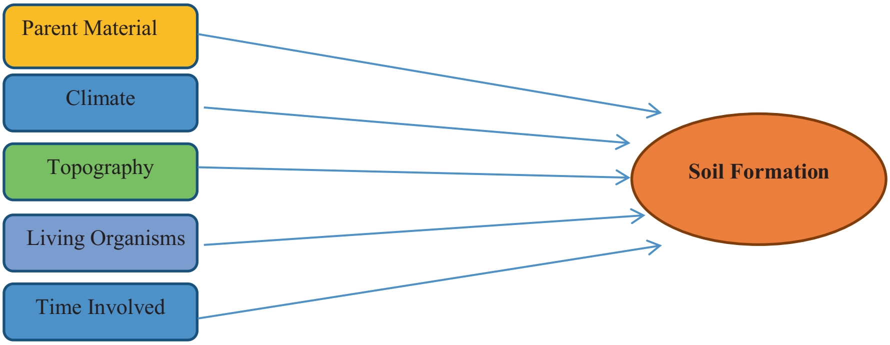
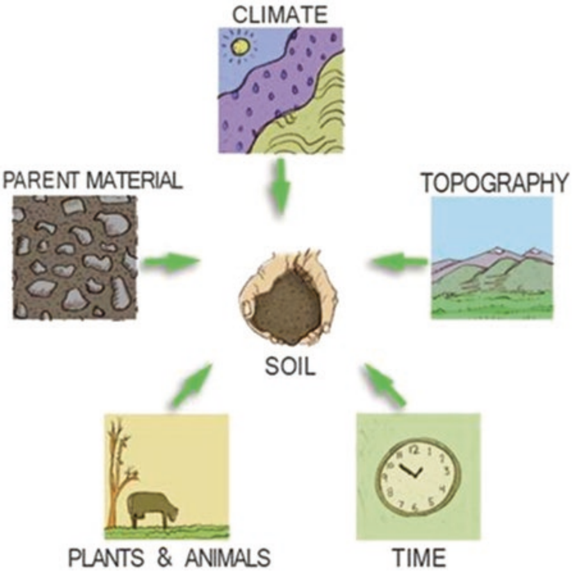


Fig. 3.2 Different determining components of soil formation

Fig. 3.3 Factors of soil formation



Soil depths tend to increase over time, but not linearly (Huggett 1998) and not uniformly (Heimsath et al. 1997, 1999, 2001a, b, 2010). The weathering and erosion of the bedrock are two main processes that affect the depth of the soil. Disruption is the slow disintegration of rocks to produce materials that form the floor, while erosion transports the detached materials, reducing soil depth. The details of the soil erosion process determine if the depth of the ground is reduced at a given site; as long as the divergence of land flow is positive, there is a net transport of land far from a point. Depth is decreased if net transport outside the site is larger than land production on the site. Since the sediment transport depends to a large extent on the relief (Montgomery and Brandon 2002), high erosion rates lead to reduced thickness to topsoil in high-relief regions. Relief affects soil formation in several ways:

- It influences the thickness of the soil profile, i.e., as the inclination angle increases, the risk of erosion also increases.
- It has an effect on the climate, which is also a factor in soil formation.
- It has an effect on the runoff, percolation, and mass movement.
- It influences the appearance that creates microclimatic conditions.

The character and chemical composition of the parent material play a crucial role in finding soil properties, particularly during the initial stages of development. The original material can influence the soil in different ways: color, weaving, structure, mineral composition, and permeability/drainage.

India has a large variety of parent material that is generally classified into the following six classes:

- Crystalline and metamorphic rocks
- Cuddapah and Vindhyan rocks
- Gondwana rocks
- Deccan basalts
- Tertiary and Mesozoic sedimentary rocks of extrapeninsular India
- Recent and subrecent rocks

Climate is the single most significant factor in the soil formation process. The temperature and precipitation influence the wear rate of the original materials and, therefore, the properties of the soil, such as mineral composition and organic matter content. High temperature favors the rapid decay of organic matter and rise in microbial activity in the soil, while low temperature causes leaching by decreasing evaporation and promoting the deposition of the organic matter, retarding the decomposition process and the effectiveness of erosion, the amount of water that filters through the soil, and the type of microorganisms present in it. The various active parts of the soil ecosystem are flora and fauna, including microorganisms. Earthworms are the most important of the fauna that forms the soil in the temperate regions, being helped in variable measure by little arthropods and enormous digging animals, e.g., rabbits, moles, etc. Semiarid regions are a subtype of dry areas with a dryness index (i.e., a ratio of the annual total precipitation with potential evapotranspiration) between 0.20 and 0.50 (Lal 2004). Soils in the semiarid regions have often been degraded by the historical use of the earth, resulting in low soil organic carbon (SOC) content and poor soil structure. The main threats to soils in semiarid regions include erosion, salinity, and degradation due to human activities (FAO 2016). These processes are linked to a deterioration in the soil structure, to a consequent loss of storage, and to the quality of the ground water and atmospheric greenhouse gas (GHG) emissions. In combination, these processes lead to desertification, a biophysical process guided by cultural, socioeconomic, and political factors (Safriel et al. 2006; Lal 2009; Meena et al. 2016a), accelerated by the extreme climate induced by climate change events and associated processes of soil erosion and salinization (Boix-Fayos et al. 2005; Gogoi et al. 2018). In turn, it leads to the displacement of human populations, since they abandon nonproductive lands and shift to more productive region, which exerts greater pressure on natural resources. Despite these sensitivities, semiarid soils are considered "hot spots" because of their importance for agricultural production and human food security. Highlighting its potential as a C sink, as well as its importance for the global cycle of C and its role as climate regulators, semiarid ecosystems have been shown to contribute most to the inter-annual variability of the terrestrial CO_2 sink with 57% (0.04 P C year^{-1}), while the global one is 0.07 Pg C year^{-1} (Ahlstrom et al. 2015). Poor management of the semiarid soils is currently a source of greenhouse gases. Increased risk of drought and inter-annual variation in precipitation associated with climate change presents particular risks for water and semiarid temperature-sensitive ecosystems (Kottek et al. 2006; Sommer et al. 2011; Kumar et al. 2017b).

3.3 Soil-Forming Processes

Soils are highly complex materials, consisting of different types of mineral particles, decomposing organic substances and microbial organisms. These constituent particles are formed into clusters of soil, which create the soil structure with its narrow arrangement. Therefore, the soils are mostly porous matter, with considerable soil properties, which provide the physical shape in which the soil processes are produced (Ritz and Young 2011; Layek et al. 2018). The formation of the soil structure helps to determine the functions of the soil and the ecosystem services throughout the life cycle of the soil from the initial formation of the soil through the phases of peak production up to the degradation of the soil that can occur through the use of the soil excessively intensive land (Banwart et al. 2011; Dadhich and Meena 2014). Usually under natural conditions, soil formation is considered a very slow process, for example, in the temporal scales of the interglacial highs until it reaches to productive state in which they can provide various ecosystem services for human beings (Strahm and Harrison 2008). The deterioration of the structure of the soil and the loss of the physical stability usually lead to the erosion of soil surface. In severe cases, this guides to the superficial exposure of the original materials (PM), as observed in the south and north of China (Zhang et al. 2004; Liu et al. 2011) and in various places in the world (Lal 2003; Quinton et al. 2010; Dhakal et al. 2015). If the land is degraded, it is difficult to restore to its previous production status (Chazdon 2008), and its degradation can cause permanent destruction of soil functions. Therefore, the pressures of a growing human population, changes in land use, and the intensification of human intervention generate significant interest about the fact that soil formation can continue to happen uninterrupted or accelerated (Wilkinson and Humphreys 2005; Haygarth and Ritz 2009). In spite of this interest, there are very few studies examining the development of the soil structure in the initial phase of soil formation (Schulz et al. 2013; Andrianaki et al. 2017) compared to the numerous amounts of studies examining soil well-developed subject to soil degradation. Moreover, compared to the success of the restoration of ecosystems on the ground, our view of soil formation, in particular the formation of soil structure in the context of restoration of vegetation, remains very poor (Griffiths 2008; Harris 2009). A crucial issue is to what extent and how rapidly agroecological measures can improve the formation of soil structure in the early stages of soil formation from the original material, as contribution to the ecological restoration techniques.

The four main processes that change the main material in the soil are additions, losses, translocations, and transformations.

(a) *Leaching*: Leaching consists of removing soluble components from the soil column. This process can also be called chemical eluviation. It is common in humid climates.
(b) *Eluviation*: It is the process of taking away of constituents in solution or suspension by the percolating water from the higher to bottom layers. Eluviation process forms eluvial horizon (horizon A_2 or E).
(c) *Illuviation*: This is the deposition or accumulation of materials that have been dragged from the upper layer to the lower horizon of the soil through the process of eluviation. The horizons formed by this process are called illuvial horizons (horizon B) (Fig. 3.4).
(d) *Podsolization*: This is the process of eluting iron oxide and aluminum (sesquioxides). The process usually occurs in areas where precipitation is greater than evapotranspiration. This occurs in cold and wet regions where leaching predominates.
(e) *Gleying*: The term glei is of Russian origin and means blue, gray, or green clay. The thickness occurs under anaerobic conditions impregnated with water when the iron compounds are reduced and removed from the ground or segregated as patches or concretions in the soil. It is mainly seen on gentle slopes and in depressions where the underlying rock is impermeable.

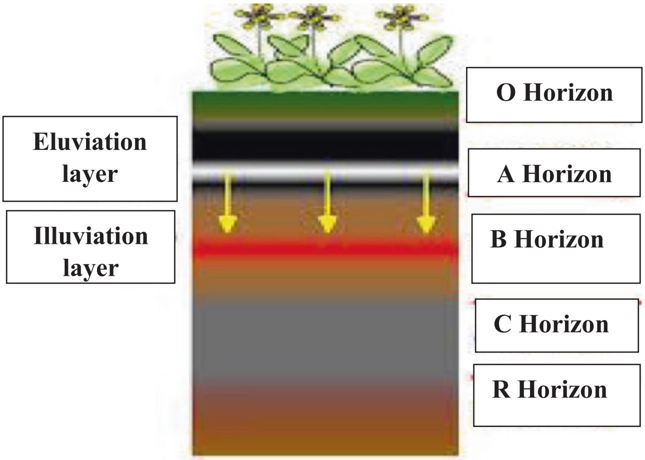


Fig. 3.4 Different layers of soil. (Modified from Pidwirny (2006))

3.4 Soil Classification

Although often not recognized as important, soils are complex and dynamic ecosystems that support the physical processes and chemical transformations that are vital to terrestrial life, making soil health and its biodiversity of vital importance to human beings. The land serves as the main basis for biodiversity on earth, as the soil contains more species than all other assembled terrestrial biotics (Blum 2005). A handful of soil can contain more than ten billion bacteria containing thousands of different species (Torsvik and Ovreas 2002), and the wildlife activities of micro, meso, and macro are fundamental foundations for biodiversity in general (Wolters et al. 2000). Furthermore, soil genetic diversity is a source of many pharmaceutical products and current and potential medical treatments in the future (D'Costa et al. 2006; Turbe et al. 2010; Yadav et al. 2018a). Soils play an important role in the earth's water cycle. Absorb, filter, and conserve water, attenuating water flows. The soils provide nutrients, water, and a physical environment conducive to the production of terrestrial biomass. In turn, biomass production is the basis of economic activities in various agroecosystems, for example, agriculture and forestry. Humans also consume soil animals (Decaens et al. 2006) and even the soil itself (Abrahams 2012). Indeed, the importance of soils in human food production systems is demonstrated by the fact that over 99% of all food (calories) consumed by humans come from terrestrial ecosystems (Pimentel 2000). Soil degrade and decompose organic matter, and when they function properly, they also have the ability to degrade or reduce toxic or hazardous compounds (Andrews et al. 2004; Dominati et al. 2010; Meena et al. 2018c). According to ICAR (Indian Council of Agricultural Research), the soils are divided into eight categories. They are (I) alluvial soil, (II) black/regur soil, (III) red soil, (IV) laterite and lateritic soil, (V) forest or mountainous soil, (VI) arid or desert soil, (VII) saline and alkaline soil, and (VIII) peaty and marshy soil (Fig. 3.5).

3.5 Soil Erosion

Soil erosion is the process of removing the upper layer of soil from agents such as wind and water. The upper soil has almost all the nutrients needed for the growth of a plant. With depth, soil fertility decreases. Therefore, erosion results in reduction of fertility of the soil by washing away the top fertile layer. The soil erosion caused by water and wind is much faster than the formation of soil. So, once the fertile soil layer is lost, it takes a lot of resources and time to restore it. The more practical measure to minimize the effect of soil erosion is its prevention. It takes small time and consumes more resources. In case of India, soil erosion problem is particularly serious due to an excessive agriculture dependence and improper management of land. According to Rama Rao (1962), soil erosion is the slow death of the soil. When the rate of soil removal exceeds the soil formation rate, soil erosion occurs. "Soil erosion is essentially a problem created by man and also faced by man himself." Soil degradation and erosion are global problems and pose major problems in

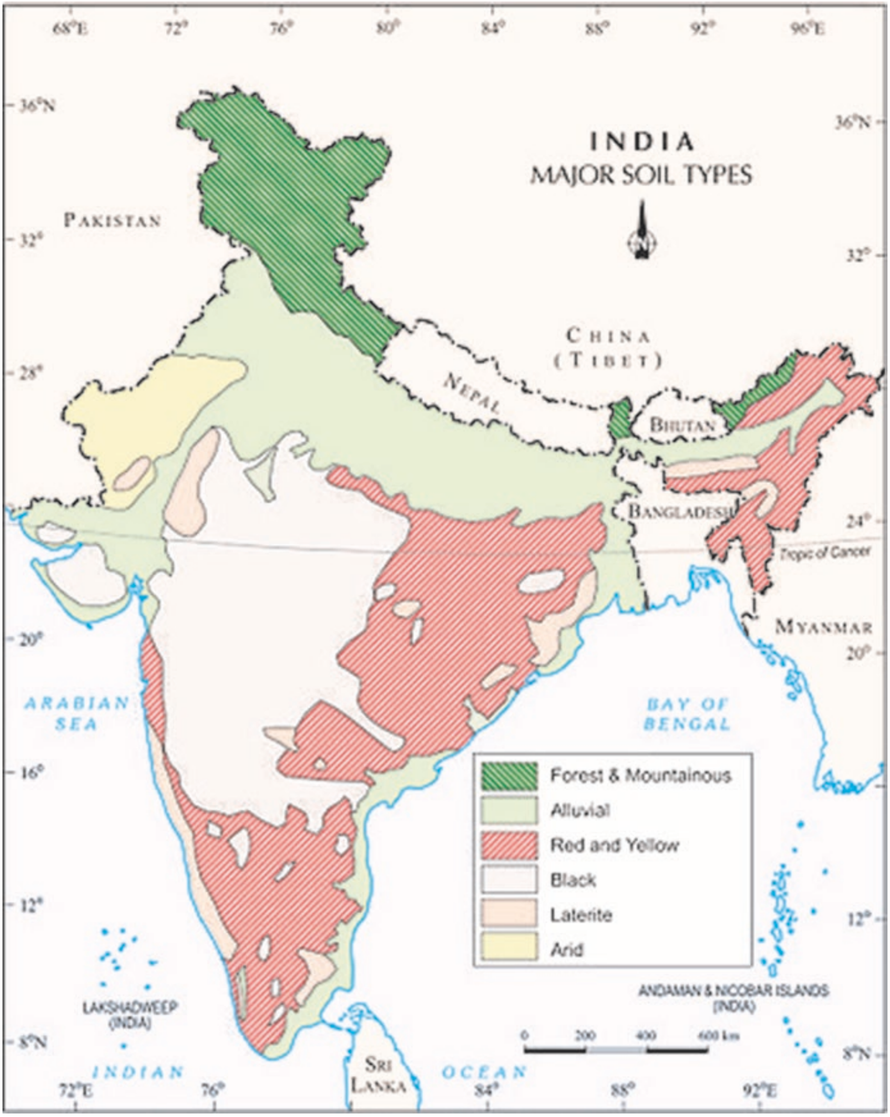


Fig. 3.5 Map showing distribution of various soils. (Source: Maps of India.com 2018)

many countries. The risks concern both urban and rural areas. In turn, these problems have serious socioeconomic and environmental impacts (Guerra et al. 2014). It is crucial that the land be preserved for future generations. Even though due to natural phenomenon erosion occurs, human activities often accelerate the process of erosion. Erosion can take place naturally due to the angle of slope and precipitation. Some surveys are an example of this, often based on stratigraphic and archaeological evidence in the bottom valley deposits. For example, the erosion of natural soil was rebuilt in northern Germany as the early Holocene, during which the soil was formed under natural forests, to the High Middle Ages, when soil erosion amount was still too small (Bork 1989). Furthermore, Dreibrodt et al. (2010) has discussed erosion during the Holocene. During the Neolithic period, many areas of the soil power plant in Europe were swept downhill due to soil erosion and struck watercourses, which led to the formation of alluvial and colluvial deposits. The climate regimes have an important role both in erosion and in process of mass movement. As for rain over a prolonged period, most soil erosion occurs during events of magnitude and moderate frequency since catastrophic occurrences not so frequent as to cause a lot of net soil erosion. This can happen in short time: When major events occur, the loss of soil is much greater in case of moderate rain. Heavy rainfall is the main cause for the engraving grooves in various landscapes (Dreibrodt and Wiethold 2015; Meena et al. 2015c). The same happens with mass movements, taking into consideration the important factors influencing the geomorphological process (e.g., the angle as well as shape of the slope, the properties of the soil, the vegetation cover, the depth of the soil, the interface between the ground and the underlying rock, the separation of vegetation, the human factors (e.g., sloping slope cuts), the absence of drainage of soil and wastewater, and the unpaved roads). In the long term, the relationship between landslide activity and trigger mechanisms can be found by the temporal grouping of dated landslides (Borgatti and Soldati 2010; Meena and Lal 2018). Voetberg (1970) and Morgan (1980) have shown the effect of various soil conservation measures on the detachment and transport of soil particles in the soil erosion process, mentioned in Table 3.2.

Table 3.2 Effect of various soil conservation measures on the detachment and transport of soil particles in the soil erosion process

	Control over					
	Rain splash		Runoff		Wind	
Measures	D	T	D	T	D	T
1. Agronomical measures						
Covering soil surface	sc	sc	sc	sc	sc	sc
Increasing surface roughness	nc	nc	sc	sc	sc	sc
Increasing surface depression	mc	mc	sc	sc	nc	nc
Increasing infiltration	nc	nc	mc	sc	nc	nc
2. Soil management						
Fertilizer, manures	mc	mc	mc	sc	mc	sc
Subsoiling, drainage	nc	nc	mc	sc	nc	nc
3. Mechanical measures						
Contouring, ridging	nc	mc	mc	sc	mc	sc
Terracing	nc	mc	mc	sc	nc	nc
Shelterbelts	nc	nc	nc	nc	sc	sc
Waterways	nc	nc	nc	sc	nc	nc

D detachment, *T* transportation, *sc* strong control, *nc* no control, *mc* moderate control

3.5.1 Causes of Soil Erosion

Soil erosion agents could be wind, water, ice, waves, and gravity, depending on external dynamics agent that generates posting, transport, and deposition of soil particles (Junge et al. 2006). The speed and extent of soil erosion are influenced by the intensity of rainfall, runoff, gradient, gradient length, vegetation, and control treatments. Soil erosion is affected by natural and anthropogenic factors; natural factors affecting soil erosion are the soil plot, the soil structure, intensity of the rain, slope, type of terrain, climate, erosivity, erodibility, and the degree of land cover with vegetation, but above all, anthropogenic factors, through actions such as land cultivation, deforestation, and construction, are more serious (Kirchlof and Salako 2008; Varma et al. 2017). Adaptation refers to the adjustment process, a current or planned climate change, and its impacts (Quandt and Kimathi 2016). The appropriateness of a particular adaptation strategy depends largely on time and place, since they are influenced by the cultural and indigenous world observations and practices (Obert et al. 2016). Some of the adaptive strategies to reduce the effects of soil erosion include the displacement of cultivation, planting in high mounds, and avoiding deep plowing. Bukari (2013) revealed that the farmers who successfully applied the traditional methods have improved their production levels territorially and the standards of life of their families. The various mathematical relationships developed between soil erosion (E) and length of slope (L) by different researchers are shown in Table 3.3.

3.5.2 Effects of Soil Erosion

Soil is an important natural resource that when effectively managed could increase the means of subsistence of homes in sedentary farming communities (Bukari 2013). Soil erosion is recognized as one of the most serious environmental problems in the world. All over the world, about 80% of the current degradation of agricultural land is caused by soil erosion (Mohamed 2015). Jing et al. (2005) thought that soil erosion is a serious environmental, economic, and social problem and that not only does it cause soil degradation and soil productivity loss but also threatens the stability and health of society in the global and sustainable development of rural areas. Shougang and Ruishe (2014) have thought that the terrain erosion is one of the most serious environmental problems in today's world because it threatens agriculture and also the natural environment. Soil erosion in Africa, the continent as a

Table 3.3 Various mathematical relationships developed between soil erosion (E) and length of slope (L)

Researcher name	Equation
Kornev and Mukhamadullina (1994)	$E = f(L^{0.5})$
Zing (1940)	$E = f(L^{0.6})$
Musgrave (1947)	$E = f(L^{0.5})$
Wischmeier and Smith (1978)	$E = f(L^{0 \text{ to } 0.9})$

whole, has caused an average annual harvest yield drop of 8.2 and 6.2% for sub-Saharan Africa and that if soil erosion rates continue unabated, the average food production will decrease in the future (Pimentel 2006). Soil erosion is a natural geomorphological process that results in water and land interactions but accelerated to become an environmental hazard due to human activities involving cutdown of forests for cultivation, poor agriculture practices, and the invasion of marginal lands (Farayi 2011; Mitran et al. 2018).

3.6 Types of Erosion

It is broadly classified into two types:

(a) Geological erosion
(b) Accelerated erosion

(a) *Geological erosion*

It is also called as normal or natural erosion and refers to the genesis and loss of soil simultaneously that maintain the equilibrium between formation and losses. It takes a long time. It is said to be in equilibrium with the soil-forming processes. The various topographic features such as the existence of flow channels, valleys, etc. are the result of geological erosion.

(b) *Accelerated erosion*

It is an excess of geological erosion and is caused by natural or man's activities due to variations in natural cover or in soil conditions. It takes place by the movement of gravity, wind, water, and glaciers. Accelerated erosion depletes soil fertility in agriculture fields. Its rates are higher than geological erosion (Suresh 2012). Water and wind are the main agents that cause accelerated erosion. Therefore, it is classified as:

3.6.1 Types of Accelerated Soil Erosion

3.6.1.1 Water Erosion

It is the movement of the ground by rainwater that flows rapidly on the surface of the exposed earth. It is divided into erosion of the rain, hill erosion, erosion of the flow, erosion of the ravine, and erosion of the current. Soil water erosion is a complex process during which the soil of the fertile soil is detached, transported, and deposited in another place. It causes the leaching of nutrients, the deformation of the soil surface, and the deterioration of water quality in the basins, as well as the sedimentation of water structures and water supply and drainage systems. Even slight erosion affects the conditions and yield of crops, prevents agrotechnical treatments, and can exclude the entire area affected by agriculture (Halecki et al. 2018; Datta et al. 2017a). The intensity of the erosion events is determined by the physiographic and hydrological factors that prevail in a specific catchment area and the use of land and vegetation cover (Podwojewski et al. 2008). It also depends to a large extent on geological factors, soil type, and climate (Nadal-Romero et al. 2008).

3.6.1.2 Wind Erosion

The process of detachment and deposition of soil particles by the action of wind is called wind erosion. In India, it happens in Rajasthan. The arid and semiarid regions where the annual rainfall is lower are those that predominate most for wind erosion. Sand dune formation occurs due to wind erosion. Wind erosion is an important factor in soil deterioration, particularly in arid areas of the world (Lal 2001; Ravi et al. 2010; Meena and Yadav 2015) (Fig. 3.6). The erosion and emission of dust are responsible for the organic carbon losses from the soil and the reduction of soil nutrients (Li et al. 2008; Webb et al. 2012; Chappell et al. 2013; Verma et al. 2015b), influence on land productivity (Sterk et al. 1996; Lal 1998) and influence the cycles and the global terrestrial and marine biogeochemical and marine climate (Jickells et al. 2005). Near the completion of 100 years, arid areas are believed to rise to spread to 50% of the earth's surface. The increase in aridity, fueled by rise in temperature and a quickly growing population, is expected to augment soil deterioration and reduce food security, especially in arid areas of developing countries. Measuring and monitoring wind erosion controls can ease detection and forecasting of soil deterioration, making a basis for better management of land and understanding the impact of leeward dust (McTainsh et al. 1990). Detection and forecasting remain difficult prospects for large-scale monitoring and evaluation (from regional to national) (McTainsh et al. 1990). In improving wind erosion and dust emission model capabilities, remote sensing has been instrumental and has been used to

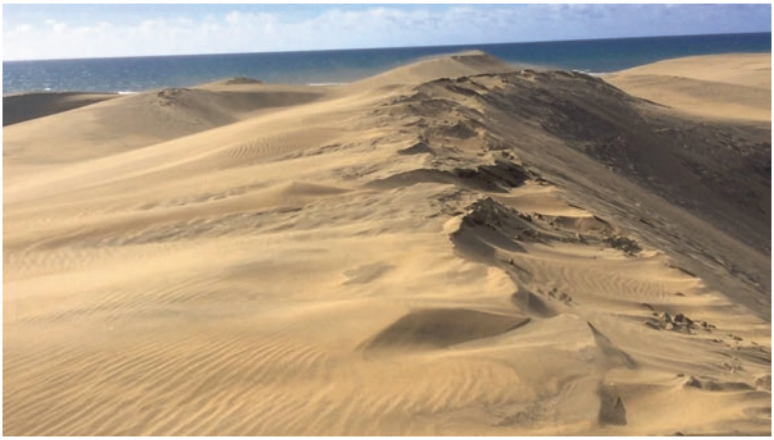


Fig. 3.6 Desert view of an area prone to erosion**.** (Source: Anonymous 2010)

inform management policy (State Environmental Committee 2011). These models need information on the structural characteristics of both soil as well as vegetation that reduce the aerodynamics of the earth's surface and the vulnerability of soil to erosion. The most effective models exploited is the multi-time remote sensing data to represent the dynamic state of the earth's surface that influences the position, erosion timing, and emission of dust (Marticorena and Bergametti 1995; Shao et al. 2000; Meena et al. 2017a). The additional integration of remote sensing and GIS with the models of wind erosion is expected to enhance model accuracy and substantially decrease uncertainty in forecasts. The fundamental causes of wind erosion are as follows: (I) The soil is dissolved, finely divided, and dried. (II) The floor surface lacks friction (smooth) and is bare. (III) The wind is powerful enough to separate the soil particles from the surface of the soil.

3.6.1.3 Raindrop Erosion

The raindrops falling on the surface are responsible for the erosion of the soil. Raindrops striking on the surface of land cause detachment of soil particles and are carried with flowing water. It is also known as "splash erosion." The ground can be splashed into the air up to a height of 50–75 cm depending on the size of the raindrops. Ellison reported that a gradient of 10% of land would result in 75% of the sprayed soil transported along the slope and 25% on the slope. A larger amount of soil material is sprayed toward the slope due to gravity, relative to the slope. Spray erosion initiates with the decomposition of soil masses into small fragments (Shainberg et al. 1992; Legout et al. 2005; Kumar et al. 2018a). In the raindrop erosion, the stability of aggregate mainly depends on changes in rain properties (Kinnell 2005; Ghahramani et al. 2012), e.g., the size and shape of the drop, the kinetic energy, the intensity, and its different combinations (Jayawardena and Rezaur 2000; Mena et al. 2002). Many studies have also stated that the raindrop impact could directly knock down soil clusters and soil erosion initiates (Ekern 1951; Kinnell 1990; Van Dijk et al. 2002). Although the properties of rainfall are important factors for influencing erosion due to splashes, as by Nearing et al. (1987), the raindrop was having impact pressure only from 1 to 3 atm. So, it is yet not certain that the impact pressure of the raindrop is forceful enough to plainly destroy the soil clusters. However, the erosion of the sketches is also influenced by the properties of the soil, such as the clay content, the organic carbon of the soil, the water content, and the cation exchange capacity in the soil (Le Bissonnais and Singer 1992; Le Bissonnais et al. 1995; Wuddivira et al. 2009; Meena et al. 2017c) (Fig. 3.7).

3.6.1.4 Sheet Erosion

It is defined as detachment of the fairly uniform layer of soil from the land surface by the action of rainfall and runoff. Leaf/sheet erosion may not be evident (Fig. 3.8), but the soil under erosion of the leaves loses a fine layer of upper fertile soil every time. The flowing water moves in the form of a thin layer on the surface of the ground called the flow of leaves. It moves at a very slow pace.

Fig. 3.7 Factors affecting soil erosion

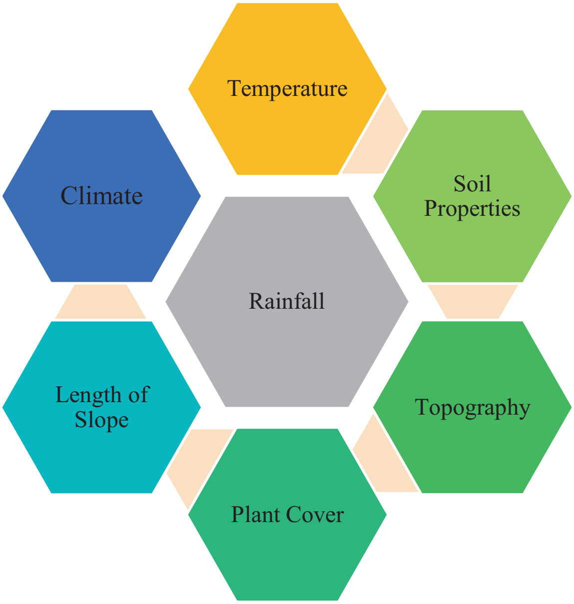


Fig. 3.8 Sheet erosion. (Image Source: USDA-NRCS 1999)

3.6.1.5 Rill Erosion

Rill erosion is also referred to as micro-channel erosion. Rill erosion is the elimination of the soil by the flowing water, forming areas of small branched canals. It is a second phase of erosion and is considered as a transitional phase between the erosion of the sheet and the gully/ravine. The shallow groove can be a work in an ordinary way. These flows are usually leveled each year by normal agricultural operations. Rill, and therefore soil, erosion depends mainly on the composition of

Fig. 3.9 Rill-eroded field. (Source: Mulaudzi 2011)

the soil and topographic features of the earth. The erosion of the stream usually begins to appear on the bottom of the slope. The detachment and transport of soil particles are relatively greater in the erosion channels. In the erosion areas of the film and reticulate, the soil separation is mainly due to impact of the drop, while sediment moment occurs mainly by a narrow surface flow influenced by the drop. Kinnell (2005) suggested six modes: (1) raindrop splash, (2) induced drop rolling, (3) saltation for induced drop, (4) flow duct rolling, (5) flow-driven saltation, and (6) suspension (Fig. 3.9). These ways of transport can take place simultaneously in series or in parallel, depending on the change of the depth of the flow in space or in time. When no outflow occurs, transport is done through the raindrop. Later when outflow occurs, the ultrathin foil flow is usually capable of carrying away detached without impact stimulation of the drop by flux shear stress-limited particles. The transport by rolling and/or salting induced by raindrops is a main mode of transport when the flow is very low, what is called rainfall-induced flow transport (RIFT) from Kinnell (2005) or rain-driven transport from Asadi et al. (2007). When the depth and flow velocity increases, the intercalated flow has the ability to transport the separated materials downward in revolutions or jumps without the requirement to stimulate the raindrop (the so-called flow-driven transport). RIFT, although more efficient compared to raindrop, is a limited transport system (Kinnell 2005; Yadav et al. 2017a). Flow-guided transport can become a dominant system on steep slopes and is more efficient than RIFT (Kinnell 2000). Transportation for suspension includes rain-guided transport as well as guided flow.

3.6.1.6 Gully Erosion

It is the advanced stage of the erosion of the furrow. It is the last phase of water erosion. When furrows are not cured, they grow in size and become ravines. The speed and degree of development of the canal are directly proportional to the velocity of the outflow. The ravine can be caused by overpowering, the adoption of faulty working practices, negligence of flows, inadequate road construction, railways, etc. The erosion of ravine is prevalent in mountain regions and has sent the attention of many researchers in the Alps (Strunk 2003), in addition to other mountain ranges, the Andes (Coppus and Imeson 2002; Vanacker et al. 2003; Sihag et al. 2015), or (Chaplot et al. 2005; Wu and Cheng 2005) mountains of Asia and Africa (Morgan and Mugomezulu 2003; Moeyersons 2003; Meena et al. 2015a), widely all over the world (Kirkby and Morgan 1978). Due to lithology and climate, channel erosion is specifically prevalent in Mediterranean or tropical regions. Roose and De Noni (1998) have shown that on the steep slopes of the Mediterranean, the size of erosion, erosion of ravine surpasses the sheet erosion regarding sediment transport and land losses. Majority of the work done in the ravine and the laminar erosion refer to the cultivated areas. It seems that "most of the time, gullying processes are triggered by inadequate cultivation, overgrazing, trunks of trunks" (Valentin et al. 2005). Elsewise, it is known that the river basin and the length of slope are crucial factors in the formation of the gullies. Poesen et al. (2003) have examined a large number of studies and have shown that, in general, "the specific yield of sediments increases when the frequency of ravines in the basin increases" but decreases when the basin increases; his study showed that "there is a critical drainage area (A) necessary to produce a sufficient outflow that will cause the incision of the ravine for a given gradient of the soil surface (S)." These authors noted that changes in land use imply a decrease in plant biomass and a reduction in soil erosion resistance through soil tillage operations. According to the shape of the ravine, it has two types: U-shaped ravine and V-shaped ravine/gully.

(a) *U-shaped gully*: It is found in the flood plains, where the superficial and subsurface soils are easily erodible.
(b) *V-shaped gully*: Often, it develops in areas where the subsoils are difficult to resist to the rapid cut of the ground from the flow of the outflow. It is common in the mountainous regions. Ravines are also classified by Tejwani and Narayana (1961) as shown in Table 3.4, after having critically observed the stormy areas along most of the Gujarat rivers.

The development of gullies occurs in four stages (Fig. 3.10).

Table 3.4 Classification of ravines

S. no.	Symbol	Description	Specification
1	G_1	Very small gullies	Depth up to 3 m and width up to 18 m
2	G_2	Small gullies	Depth up to 3 m and width greater than 18 m
3	G_3	Medium gullies	Depth up to 3–9 m and width not less than 18 m
4	G_4	Deep and narrow gullies	(a) Depth up to 3–9 m and width less than 18 m
			(b) Depth greater than 9 m, width varies

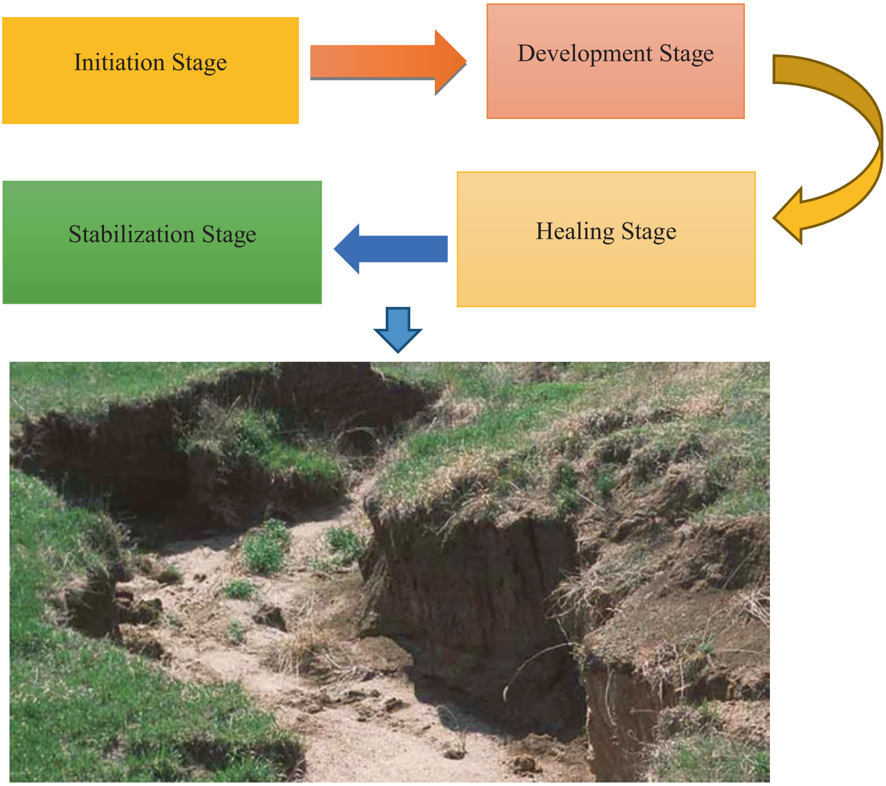


Fig. 3.10 Different stages of gully development

3.6.1.7 Stream Bank Erosion

It is the sourcing of material from the bottom and side of a stream or waterway and the clipping of bank by flowing water (Fig. 3.11). It mostly occurs due to taking away of vegetation, overgrazing, or cultivation on the area close to the stream's banks. This erosion damages neighboring agricultural lands, highways, railroads, and bridges. It is more concentrated in the rainy seasons when the volume of the outflow and its flow velocity increase. Choosing the most appropriate methods to protect the flow bank requires careful consideration of the hydraulic principles in relation to the location, design, and installation of the structures used (Murthy and Nguyen 1985).

3.7 Mechanics of Water Erosion

Water erosion has occurred since the beginning of time, but its progress has accelerated with human activities. This was mainly due to man's depilation mantle of vegetation of the native soil and its subsequent abuse and mismanagement of the land.

Fig. 3.11 Stream bank erosion. (Source: McQueeney and Leininger 2017)

Tanks and streams full of sediment canals, ravines, eroded abandoned lands, and the remains of once prosperous civilization have a silent test of the destructiveness of erosion. Water causes erosion by separating soil particles of the surface mass of soil and transporting it mainly downhill. You can observe it in any area where there are natural precipitations or where water is artificially applied to the earth's surfaces. The erosive action of water is greater and more destructive in which the protective cover of the vegetation has been removed, exposing the surfaces of the earth to the direct action of rainstorms. The movement of soil with water is a complex process. It is influenced by quantity, intensity, and duration of the rain, quantity and speed of surface flow, nature of the soil, soil cover, slope of the earth's surface, and many other factors. In any case, the erosive power of water is determined by the interaction or balance of different factors, some favorable to the ground movement and others that oppose it. Soil material first must be evicted from its position in the surface of the earth, as it can be transported. It can therefore be splashed, toasted, scrolled, or transported in suspension along the surface. These are the processes which are largely the result of the raindrop splash and water turbulence in motion (Stallings 1953). The various geological actions generated by the flow of water on the surface of the soil through which soil erosion occurs are described below.

3.7.1 Geological Actions

(a) *Hydraulic action*: When water flows over the soil surface, it compresses the soil. As a result, the air present in the voids exerts a pressure on the soil particles, which leads to the soil detachment. The pressure exerted by the air present in the voids is known as hydraulic pressure. The particles of earth detached in this process from their places are swept away by running water. Hydraulic action is more effective, especially when the terrain is free (Suresh 2012).

(b) *Abrasion*: Erosion of the riverbank from the bottom of the valley is the result of the abrasion of running water. The soil particles mixed the tap water, creating an abrasive power in the water with which the capacity of the water flow to undermine the soil particles increases. Because of this effect, larger soil particles are eroded by flowing water.

(c) *Attrition*: It includes the mechanical degradation of charges that run along the moving water due to the collision of particles between them. When fragments of rock, boulders, or large pebbles are found in the moving water of the currents or the river, they are fragmented due to the impact actions between them. The fragmented particles move together with the flowing water. They generate abrasion effects on the bottom and on the banks of the watercourse. This effect pronounces the erosion of water (Suresh 2012).

(d) *Solution*: The chemical action between running water and soil/rocks is called a solution. It occurs when the existing rocks/soil dissolve easily in the water. Because of this action, soil or rock materials dissolve in running water due to chemical action and are transported along the water stream.

(e) *Transportation*: In this process, the soil whose soil particles dissolve in tap water is transported from one place to another. The transport of particles depends on the following factors:
    - The charge rate of running water in the water
    - Impediments/obstacles present in the flow of water
    - Load capacity of running water

3.7.2 Modes of Soil Movement

During water erosion, the process of transporting the soil by running water is completed in the following ways:

(a) *Solution*: The water-soluble contents present in the water are transported by the water as a solution. Normally, some dissolved chemicals, such as calcium carbonate, etc., derived from rocks, are transported as a solution by running water.

(b) *Suspension*: The suspension process involves the transport of finer soil particles present in suspension in running water.

(c) *Saltation and surface creep*: The jump mechanism is responsible for moving medium-sized soil particles that cannot be raised as a suspension due to their large size but mix in water and flow on the bed of the stream in the form of mud. The leap and the surface fluency share a significant part of the sediment load carried by running water. The transport of soil particles through the surface sliding action occurs for the thicker dirt particles activated through the actions of jump, collision, and sliding (Suresh 2012).

(d) *Deposition*: The deposition of the mixed load in running water occurs under the following conditions:
    - When the force acting in the direction of the movement of the water and responsible for transporting the load becomes much lower than the resistant force acting in the opposite direction, the materials are deposited in the bed.

- When there is presence of surface impediments such as trees, shrubs, etc. in the flow path of running water, there is a tendency to decrease the speed of running water, and consequently, the mixed soil load is deposited in the water.
- Whenever there is a meander of the river or the stream, the velocity of the flow on the concave side of the river decreases drastically and the deposition of the charge takes place on that side (Murthy and Nguyen 1985).

3.8 Agronomical Measures of Erosion Control

Methods used to control soil erosion through crops or vegetation and through agronomic practices are called biological erosion control methods. Biological methods are used when the slopes are small (less than 2%) and the problem of erosion is not serious (Murthy and Nguyen 1985). In soil and water conservation, agronomic measurement is a cheaper, lasting, and effective technique. The agronomic conservation measures work by reducing the impact of raindrops through interception and, consequently, by reducing soil erosion. Infiltration rates also increase and, therefore, reduce surface runoff. The agronomic measures widely used for the control of water erosion are:

3.8.1 Contour Cultivation

In the cultivation of contours, all agricultural operations, such as sowing, tillage, etc., are executed in the contour of the area. Contour cultivation reduces surface flow velocity and delays soil erosion. This involves sowing crops through the slope instead of climbing and descending from the slope. Contour trimming is more effective on slopes between 2% and 10% (Suresh 2012; Meena et al. 2018a). The use of contour crops protects the precious upper soil by reducing the velocity of the outflow water and inducing more infiltrations. On a long and smooth slope, contour cutting is more effective because the flow velocity is high in this situation and the contour cut shortens the slope length to reduce the flow velocity. Crops such as corn, sorghum, pearl, and millets are suitable for growing outlines. The main purpose of growing the boundary in areas with little rain is to conserve moisture and in wet areas to control erosion. Depending on the slope of the terrain, the contour lines are located at a distance of 25–33 m (Suresh 2012). In this method, after the operations between the crops, the ridges between the crests formed in the contours maintain the outflow of water and store them in the ground. Therefore, reduce both runoff and soil erosion. The contour cultivation reduces the outflow by increasing the roughness of the surface perpendicular to the slope. The increased surface roughness reduces the speed of any flowing water, providing more time for infiltration and reducing erosion rates. Although popular as a means of reducing soil losses in many parts of the world, the cultivation of the boundary has not been widely used in the United Kingdom due to the concern that the machines will overturn in wet

Fig. 3.12 Contour cultivation

conditions. Quinton and Catt (2004) have shown potential benefits for reducing soil losses and runoff in sandy soils in the United Kingdom, but, as with minimal processing, although the benefits for reducing soil erosion are well known, there are fewer tests available to indicate the benefits of P losses (Fig. 3.12).

3.8.1.1 Strip Cropping

The cultivation of strips is the practice of cultivating different crops in alternative strips along the slope. Striped crops should be separated by growing and erosion-resistant neighboring crop strips. It is mainly used in areas where the slope length is not too long. Striped crops control surface runoff and infiltrate to preserve rainwater. The decrease in the flow velocity between the row strips is obtained by obstructing the flow path. Strip cultivation is a more intensive agricultural practice than boundary farming. The agricultural practices that are included in this type of agriculture are the agriculture of the boundary strips, the cover crops, the agriculture with conservative processing, and an adequate rotation of the crops. A crop rotation with a combination of mixed and cultivated crops, grown in contours, provides food and fodder and preserves soil moisture. Narrow-growing crops act as barriers to flow and reduce the runoff rate generated by interspersed crop strips and ultimately reduce soil erosion. Strip crop is a strategy that divides the individual fields into strips with different cultures (Lesoing and Francis 1999). The strips must be large enough to be handled independently of the existing machines but close enough to interact with the components of the strip (Exner et al. 1999). It can be considered as the adaptation of the most traditional systems of associations but allows the use of modern agricultural machinery. Generally, farmers try to seize the advantage of combining more exclusive crops (cultivating a single crop in a field) by reducing competition for resources between species that exist in the same field (Hauggaard Nielsen et al. 2009; Bedoussac and Justes 2010: Corre-Hellou et al. 2011; Verma et al. 2015c). Above all, farmers in the United States of the East and Midwest used alternating strips of corn and soya or dried beans. For several interculture systems, it has been shown that combined yields exceed the sum of the cultivated species components alone as a result of the additional use of available growth resources (Willey 1979). Often, legumes included need to rely on biological fixation because the cereal has a greater competitiveness than the inorganic soil N (and weeds) causing mineral soil N to be used for the production of grain instead of biomass weeds facing a growth of legume crops only (Hauggaard-Nielsen et al. 2001; Corre-hellou et al. 2011). However, water stress (Snaydon and Harris 1981) and light quality/shading (Tsubo et al. 2001; Jahansooz et al. 2007; Sofi et al. 2018) are the main growth parameters that influence potential complementary interactions (Lesoing and Francis 1999). The strip cutting is presented with the following names (Fig. 3.13):

(a) Contour strip cropping
(b) Field strip cropping
(c) Buffer strip cropping
(d) Wind strip cropping

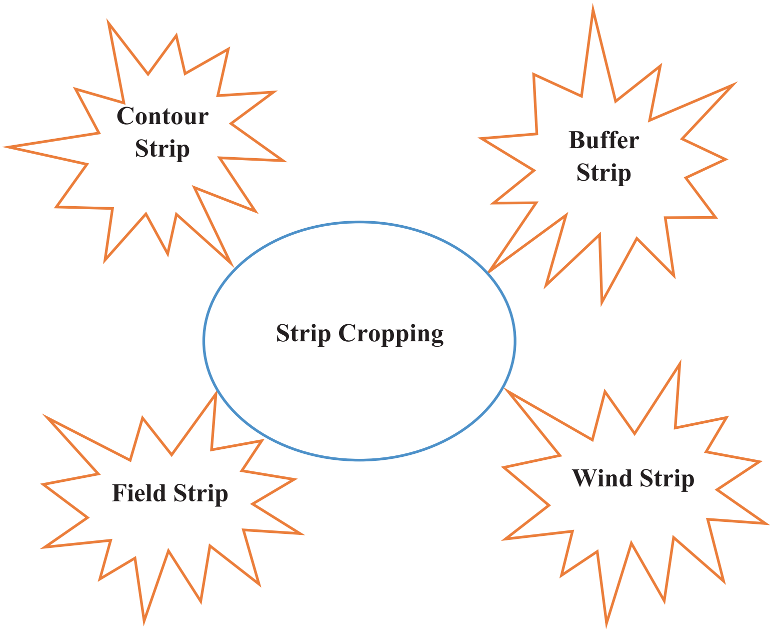


Fig. 3.13 Types of strip cropping

Contour Strip Cropping

When cutting the contour strips, the alternating culture strips are sown more or less along the contours, similar to the contour. It is adopted on a level ground through a slope instead of climbing up and down the hill to check the flow of surface water. Crop rotation and processing operations are followed during agricultural operations. The width of the strips varies according to the topography (Michael 1993).

Field Strip Cropping

In a field layout with stripes, uniform width stripes extend along the predominant slope, protecting the soil from erosion caused by water. To protect the ground from wind erosion, the strips are arranged in the predominant direction of the wind. This is a modified form of trimming of the boundary strips, in which the culture strips are positioned parallel to each other. Mainly follow areas where the topography is very irregular and the contour lines are too curved for a strictly contoured agriculture (Fig. 3.14). Field strip cultivation should be avoided in depressed areas and should be left for grass streams (Michael 1993).

Buffer Strip Cropping

In this method, the strips of herbs or vegetables are placed between the crops of regular rotation boundary strips. The cultivation in buffer strips is carried out when a uniform strip of crops is required for the correct operation of agricultural machines, while it is cultivated in a strip of level curves. The width of the buffer strips is generally from 2 to 4 m. Buffer strips provide excellent protection and effective soil erosion control.

Wind Strip Cropping

In this method, the crop strips are arranged at right angles to the direction of the prevailing winds, regardless of the direction of the slope of the land. It is used to control wind erosion. It is recommended where wind erosion is more prominent.

3.8.2 Cropping System

The adoption of sustainable agricultural practices is the most important measure for soil conservation. In many parts of India, a specific crop is planted in the same field year after year. This practice leads to the exhaustion of some nutrients in the soil making it sterile. Crop rotation is a practice in which a different crop is grown on land each year. This helps to conserve soil fertility as the different crops require different soil nutrients (Michael 1993).

3.8.2.1 Crop Rotation

Crop rotation controls the erosion of soil and weeds. It also helps to increase soil fertility and organic matter. It also maintains the soil infiltration rate. Legumes such as peanut, soybean, green gram, chickpeas, etc. are commonly used in crop rotations. Agricultural land management, including the application and use of synthetic

Fig. 3.14 Field strip cropping. (Image Source: USDA-NRCS 2017)

fertilizers, processing practices, and crop rotation systems, accounts for about 80% of the total N_2O emissions in the United States annually (Venterea et al. 2011; Buragohain et al. 2017). Nitrous oxide is directly influenced by the speed of application of N as well as the source of fertilizer and cultivation type (Eichner 1990). In the same way, technique and time of application of fertilizers and the use of other chemicals, irrigation, and N and fertilizers of residual C crops, above all, affect the emissions of N_2O (Eichner 1990). Nitrogenous fertilizer stimulates the production of N_2O to provide a substrate for N microbial conversion by nitrification and denitrification (Venterea et al. 2005; Meena et al. 2018b). Nitrification occurs when ammonia is added to the soil as a fertilizer, such as nitrogen fixation from leguminous plants or soil mineral organic matter (SOM) (Paustian et al. 2016; Meena et al. 2015e). During this microbial process, the ammonium becomes nitrite and finally nitrate, even if small amounts may be lost as N_2O (Snyder et al. 2009). In addition, under conditions of oxygen in the soil, the nitrogen acceptor used as an acceptor and

N_2O electron terminal is an intermediate step in the complete denitrification of N_2 gas (Robertson and Groffman 2007; Paustian et al. 2016; Kumar et al. 2017a). Since the spring application of fertilizers in the United States Corn Belt (Illinois, Iowa, Indiana, Ohio, Southern and Western Minnesota, and Eastern Nebraska) occurs when the saturated rains are common, the soil can easily become water, and the promotion of large-sized denitrification events in a large part of the annual flow of N_2O can occur on short time scales (Venterea et al. 2012; Dadhich et al. 2015).

3.8.3 Tillage Practices

Soil processing is the mechanical manipulation of the soil to provide an environment conducive to crop growth. Soil processing maintains soil infiltration capacity and controls weeds. It also provides aeration of the soil and also controls erosion. Due to overprocessing, the soil structure is damaged and causes erosion. Soil processing studies often have mixed results with zero (NT) or reduced to have lesser or no effect on N_2O emissions compared to conventional soil processing systems (T) (Venterea et al. 2005; Rochette et al. 2008; Snyder et al. 2009; Varma et al. 2017a). Conservation methods in agriculture are commonly seen as effective measures to protect soil from erosion (Harrold and Edwards 1974; Gaynor and Findlay 1995; Holland 2004; Meena et al. 2017b). According to Potter et al. (1995) and Torbert et al. (2001), about 30% land cover is generally used to define processing systems as "conservatives." Kassam et al. (2009) defined conservation agriculture as a concept for agricultural production which saves resources that must meet the following conditions: (1) minimum soil disturbance; (2) land cover in one of three categories, 30–60%, 61–90%, and 91% ground cover, measured immediately after the planting operation (land cover below 30% is not considered conservative agriculture); and (3) crop rotation involving at least three different crops. These definitions for conservative agriculture are also used in Naudin et al. (2010) and Prasuhn (2012). Conservation tillage methods can reduce costs and increase the efficiency of machine entry (Van den Putte et al. 2010) also for small-scale agricultural systems that prevail in Central Europe. As soil erosion adversely affects crops (Strauss and Klaghofer 2001), conservative processing methods also contribute to maintaining yield levels. Zaitseva (1970) reported the combined effect of plow and crop residues on soil erosion, shown in Table 3.5.

Table 3.5 Combined effect of plow and crop residues on soil erosion

Soil erodibility (gm^{-2} 5 min^{-1})			
S. no.	Plowing operation	In autumn plowing	In summer plowing
1	Plowing with furrow turning to 25–27 cm depth	59.2	149.2
2	Soil loosening without furrow turning or straw incorporation	22.2	48.4
3	Ditto, with incorporation of the straw	6.4	10.9

The different soil conservation tillage practices used are:

3.8.3.1 Minimum Tillage

Seedbed preparation with minimal soil disturbance is called minimum processing/tillage. It provides the right environment for the seeds to germinate. It also increases the water absorption capacity of the soil and, therefore, controls erosion. Reduces machining costs compared to conventional methods (Suresh 2012; Yadav et al. 2017b).

3.8.3.2 Strip or Zone Tillage

The nursery is prepared by cultivating the soil in a narrow strip in the area adjacent to the proposed row of seedlings. The area between the files is left untreated or carved in a different way. The environmental zone of the seedlings is the area around the planting area where the water management area is the area between the crop rows.

3.8.3.3 Mulch Tillage

It is a plowing operation, which leaves a substantial surface of the residual vegetative materials such as leaves and crop residues on the surface. It is also called mulch. Leaves, stems, and debris reduce flow velocity and thus control erosion. Mulching reduces the kinetic energy of falling raindrops. Also, they control the soil temperature. The ground mulch is a layer of dry soil formed at the top of the profile. Vertical mulching keeps vegetative stubble in trenches. It acts as a drainage tool for removing surface water from low areas (Suresh 2012).

Mulching

It is defined as the application of plant residues or other materials to cover the upper surface of the soil. The covers are used to reduce rainfall, reduce evaporation, control weeds, reduce soil temperature in hot climates, and moderate the temperature to a level suitable for microbial activity. Mulching helps break up the energy of raindrops, prevents spray and soil structure dissipation, and hinders the flow of runoff to slow down and control the erosion of the blade and the current. Mulching also helps build infiltration capacity by maintaining a conductive soil structure on the upper surface of the earth. The key factor limiting the efficient use of arable land and agricultural production is scarce water resources in arid and semiarid areas. While increasing agricultural production, it is a great challenge to minimize its ecological and environmental impacts. Cover technology has been widely applied in northern China as a water-saving practice. Fertilizer materials such as plastic film, gravel or sand, and straw for different crops and plants have been applied (Fig. 3.15), and these cover technologies have greatly improved the physicochemical properties of the soil, soil moisture, crop productivity, and efficiency of use water (WUE) (Ji and Unger 2001; Wang et al. 2009; Dhakal et al. 2016). The advantages of plastic film surface padding are the result of improved water and thermal soil conditions, such as increased surface water storage, crop growth, consumption of water and nutrients from the roots, and related performance indices including plant height, biomass

Fig. 3.15 Different mulch materials

accumulation (LAI), grain yield, and WUE (Zhang et al. 2011). It has also been shown that pebble sand mulching reduces soil erosion, decreases evaporation, and favorably reduces the fluctuation of soil temperature between day and night (Kemper et al. 1994; Li 2003; Yamanaka et al. 2004; Meena et al. 2015b). Furthermore, straw mulch has been shown to improve the relationship between soil water and crops by improving soil physicochemical properties, such as bulk density, porosity, and aggregate stability (de Silva and Cook 2003; Jordan et al. 2010; Meena et al. 2016b). Several surveys have been carried out comparing the effects of mulching on water conservation in the soil, total real evapotranspiration (ETc., T), growth of the summer corn crop, yield, WUE and crop efficiency, and precipitation use efficiency. Several periods of cultivation and mulching and irrigation levels have been considered under the plastic film and straw mulch. Furthermore, for straw and gravel mulching, different amounts of application have been considered (Jordan et al. 2010; Cai et al. 2015; Ram and Meena 2014). Cover technologies have been applied to corn seeds, spring maize, summer maize, and other grain or fruit crops (Zhao et al. 2013; Luo et al. 2015; Verma et al. 2015). In most conditions, the accumulation of water in the soil, the growth of crops, the yield and WUE use, and the precipitation use efficiency for different mulches have increased to different degrees. Correspondingly, the cumulative evaporation of water of soil or ETc, T has decreased, and results have been similar for investigations incorporating two mulching technologies for mulching, sand and gravel mulch and straw mulch.

Lal (1976) reported the effect of mulch on soil loss and runoff in uncropped land at four slopes, i.e., 1, 5, 10, and 15% as shown in Table 3.6.

Table 3.6 Effect of mulch rate on runoff and soil loss under an uncropped land

Mulch rate (tha^{-1})	Runoff (%)	Soil loss (t ha^{-1})
0	50	4.83
2	19.7	2.48
4	8	0.52
6	1.2	0.05

3.8.3.4 Contour Plowing

If the plow is at right angles to the slope of the hill, the ridges and furrows interrupt the flow of the descending water. This prevents an excessive loss of ground as it is less likely to form ravines and also reduces runoff so that the plants receive more water (Michael 1993).

Plowing the Land in Right Direction

Plowing the land in a direction perpendicular to the wind direction also reduces wind speed and protects the upper soil from erosion.

Lutz and Chandler (1946) cited the following points in support of the control of vegetation erosion:

- Water infiltration is favored by the high porosity of the soil beneath the vegetation. Water percolation helps to preserve soil moisture, accelerating the growth of vegetation.
- The accumulation of organic matter on the surface increases the water holding capacity of the soil.
- Radical vegetation systems support the soil mechanically and provide stability to the ground.
- It gives protection to the ground from the wind. Forest vegetation protects the soil from the direct effects of drought, snow, and rain.

The destruction of the vegetation cover usually causes accelerated erosion, flooding, and sedimentation. The previous victims of soil erosion tell the drastic deforestation (destruction of forests). In our country, deforestation has been recognized as the most powerful and potent cause of soil erosion, and efforts have been made to control it.

State forest departments in India have already undertaken this practice, albeit in very small areas, and have achieved good results. The forest departments of Baramulla, Gulmarg, and Banihal in Kashmir offer good examples. In the Baramulla region, mixed plantations of Pinus, Cednis, and other species have been created. The plants thrive well and have proven to a large extent the losses due to soil erosion (Gupta 2018; Yadav et al. 2017c).

In the area where no plantations have been made, the soil is actively eroding. Another example is that offered by the Sankaracharya hills in the vicinity of Srinagar, which in the past was very much eroded. Now, it has been improved by afforestation. The forest department took the planting of coniferous species such as

Pinus wallichiana, *P. roxburghii*, *P. sylvestris*, *P. insignis*, *P. gerardiana*, *Cupressus arizonica*, and *C. sempervirens*; *Juniperus species*, *Cedrus deodara*, and broadleaf species, such as *Aesculus indica*, *Fraxinus*, and *Juglans regia*. These plants control erosion to a certain extent.

Efforts have been made to control the spread of the Rajasthan desert and sowing is carried out in that region in two or three strips. Small plants are planted on the windward side and tall trees on the leeward side. *Leptadenia spartium*, *Cenchrus ciliaris*, *Balanites roxburghii*, *Calligonum polygonoides*, *Saccharum munja*, *Kochia indica*, etc., and, on the leeward side, *Acacia Senegal*, *A. leucophloea*, *Ricinus communis*, *Prosopis spicigera*, *P. juliflora*, *Parkinsonia*, etc., are growing (Gupta 2018; Meena et al. 2015c).

The problem of afforestation is the selection of species suitable for a given area. This can be achieved by dividing the entire area into different basins based on climate, soil, and biota. The species suitable for each area should be selected from those that already grow there. Knowledge of vegetation succession trends will be of great help in afforestation practices. Lutz and Chandler (1946) stated that the climax vegetation in any region is the most effective agent for preventing accelerated erosion. Afforestation also verifies the erosion of unstable rocks testing water loss (Puri 1951).

3.9 Engineering Methods of Erosion Control

3.9.1 Terracing

It is a combination of ridge and channels and is usually practiced in areas of steep slope. It is not feasible for flat and cut terrain. The terraces reduce the length of the slope by dividing the length of the slope into different parts. It is not used in those mountainous areas where the depth of the soil is not sufficient. In short, the term "agricultural terrace" is well believed, and it is that the terraces can produce a number of advantages, including limiting surface runoff and repopulating the ground, thus reducing soil erosion; increasing the depth of the soil, infiltration rate, and water retention, thus increasing the yields; and improving drainage or redirecting excess flows, mitigating erosion, and conserving and protecting dry-adapted plants. In addition to increasing the temperature of the soil, these encourage seed germination. However, it should also be clear from this brief summary that no terrace can perform all these functions: a terrace could not be designed to improve water retention and improve drainage, for example. This is not simply a matter of semantic engineering (i.e., the generic term "agricultural terrace" includes a series of structures built in different ways to solve different problems) because of a particular type of terrace, such as cutting and filling common terrace. Terrace level could be given to perform different functions, even within the same slope: exposed to an increase in soil temperature in one place while in the shade and under other watering. Analysis of the profitability of reporting positive results for the construction of terraces at a particular time and place (Bizoza and De Graaff 2012; Tesfaye et al. 2016; Meena et al. 2014) must be taken in context and produce conclusions that cannot, of course, be easily transposed into another moment and place. The terraces in India are classified into two types:

3.9.1.1 Bench Terraces

They advance as fields built along the contour of the earth half cut and half fill. The steps are also used for cultivation purposes. In general, it is practiced on steep slopes of 16–33%. According to Rama Rao, the terraces of the benches can be "table" or tilted outward or inward with or without a slight longitudinal slope (Fig. 3.16).

(a) *Level bench terrace*: Generally used in areas that receive average rainfall and have highly permeable land. It is used for the cultivation of rice.
(b) *Bench terraces sloping outward*: They are used in areas with low rainfall and permeable soil.
(c) *Bench terraces sloping inward*: It is used for stagnation-sensitive crops, such as potato. It is used in less permeable soils with heavy rains.

According to Bali (1978), depending on the purpose, bench terraces are classified into:

(a) *Hill-type bench terrace*: Used in mountainous areas that have an inverse slope toward the hill
(b) *Irrigation-type bench terrace*: Level benches are used in irrigation conditions. The level table-type terraces are referred to as irrigated bench terrace.
(c) *Orchid-type bench terrace*: They are built in the form of narrow strips and are also called intermittent terraces and step terraces.

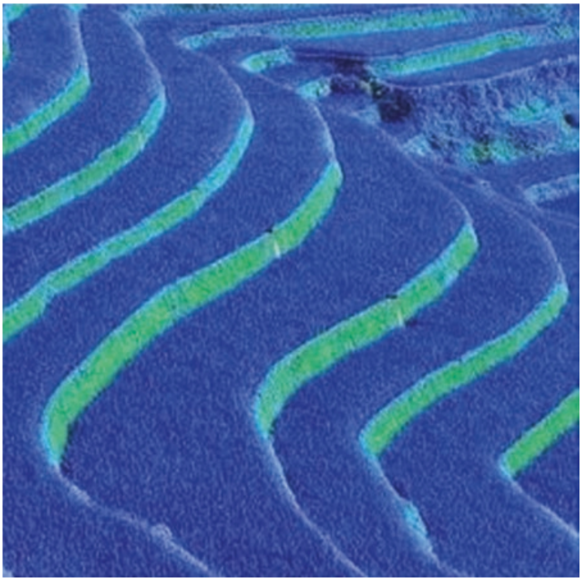


Fig. 3.16 Terraced field

3.9.1.2 Broad Base Terraces

A large terrace is the construction of a surface canal or type of embankment, which is formed through the slope of the land. It is classified into two types:

(a) *Graded terrace*: They are built at suitable intervals along graded contours in a slight slope. It reduces the length of the slope, which in turn reduces erosion. It is used when the slope of the land is between 3 and 10%.
(b) *Level terrace*: The flat terraces are used in the case of low to moderate rainfall and the slope of the land is less than 6%.

3.9.2 Bunding

It is a type of embankment structure built to control runoff and minimize ground erosion by reducing the length of the pitch. It is suitable for land with a gradient of 2–10%. Bunds are not suitable for black soils as they develop cracks. The inland valleys make up more than 38% of the total number of wetlands in sub-Saharan Africa and are widely cultivated with rainy rice in wetlands. Rainfed plateau grown on or slightly inclined, without walls or means, which are flooded with rain and underground during part of the rice growing season, although in some season's fields do not flood due to lack of rain. The level of performance in the company is generally low due to various biophysical and poor crop management practices (Datta et al. 2017b). Moreover, in the internal valleys, natural resources (in particular water and soil resources) are strongly correlated with their position in the topographic sequence (Homma et al. 2003). Therefore, a better understanding of the determinants of performance in rainforest rice crops is a prerequisite for the development of good agricultural practices. The main difference between Asia and West Africa in rice cultivation in the lowlands is that most of the fields in West Africa do not have water control, such as dams or drainage system. Bunds have been shown to improve productivity by 30–100% of the increase in the harvest in Tanzania (Raes et al. 2007). If the rain is too abundant or too intense to be absorbed by the ground, it must be collected to trap runoff water before it collects enough energy to discharge (Roose 1996). Given the roughness of the soil surface, the micro terrain survey, and the risk of damage due to excessive rain, we recommend a batch height of 0.3 m for lots of maximum 0.10 ha. In Karnataka, for grouping purposes, the soils are classified according to the appropriate depth for the construction of the beams, with the exception of some red soils, as shown in Table 3.7.

Bunds are called contour bunds when they are built in the outline and are called "graded bunds" when a grade is given on them.

(a) *Contour bunds*: It is adopted in all types of permeable land. It is suitable in agricultural land where the slope is around 6% and in areas where average annual rainfall is <600 mm. It is not used in clay soils. The contours of the contour can be narrow or wide (Suresh 2012).

Table 3.7 Classification of soil according to the depth of the construction of the beams in Karnataka

Class	Soil depth (cm)
Very shallow	Less than 7.5
Shallow	7.5–22.5
Medium	22.5–45
Medium deep	45–90
Alluvial deep	45–90
Deep(heavy clay) black soils	More than 90

Source: Singh and Kanwar (1991)

Fig. 3.17 Grassed waterways. (Source Suresh 2012)

(b) *Graded bunds*: Used when the average annual precipitation is >600 mm. It reduces the length of the slope and, as a result, reduces erosion. The assessment must be within the non-erosive limit. It is not recommended when the rating is less than 2% or more than 8%.

3.9.3 Grassed Waterways

They are natural or artificial watercourses, covered with erosion-resistant grasses and used to divert surface water from agricultural land (Fig. 3.17). They are built along the slope of the land. Grass canals are used to eliminate natural runoff or to transport sewage from contour furrows and to bypass channels or as an emergency dump into agricultural ponds (Suresh 2012).

Singh and Kanwar (1991) have also cited the following values of non-erosive velocity, for safe design of grassed waterways as shown in Table 3.8.

Table 3.8 Permissible velocity for safe design of grassed waterway

Permissible velocity (m sec^{-1})	Cover condition
0.9–1.2	Sparse grass cover
1.5–1.8	Good grass cover
2–2.5	Sod of excellent cover

Fig. 3.18 Check dams near Hatiwara, Awantipora J&K

3.9.4 Check Dam

It is a small barrier made of stones, sandbags, etc. which reduces the velocity of flow and thus reduces erosion. They may be permanent or temporary (Fig. 3.18). The water stored increases soil moisture of the adjoining area and allows percolation to recharge the aquifers. Check dam minimizes risk of submergence of cropped lands during flash floods (Suresh 2012).

3.10 Measures Taken to Conserve Soil in India

In India, to reduce soil erosion measures, such as the formation of contour lines, regulation of forestry, mixed farming, crop rotation, and grazing control have been adopted. Some of the schemes/measures initiated by the central government for soil conservation like;

During the five-year plan, the central government has established the division of land and water conservation in the department of agriculture and cooperation, which aims to provide a general perspective of problems such as water and wind erosion (Annon 1974).

- The central government has initiated a plan in the 7th FYP (five-year plan) for the regeneration of alkaline soils.

- The water basin development project in shifting farming areas was launched in seven northeastern states during the 8th FYP.
- The central government has started planning for the management of the River Valley project basin and flood-flooded rivers in the 9th FYP (Anonymous 1979).
- The central government has initiated the ravine recovery program in some states such as Rajasthan, Madhya Pradesh, etc.
- Although the government has launched several soil conservation projects, its implementation is not up to par. Therefore, it is necessary to educate people, especially people in villages, on soil conservation methods.

3.11 Soil Loss and Its Estimation

Loss of soil occurs in areas affected by different types of erosion. Nutrient loss also occurs with loss of soil. The estimate of the loss of soil is necessary to know the influence of the different land management practices. The flow diagrams are used to measure the loss of soil due to sheet erosion. Combined H-fume and Coshocton samplers are used to estimate runoff and sediment for small agricultural water basins. Several scientists have proposed various equations to estimate the loss of soil. These equations had some limitations. Finally, Wischmeir and Smith in 1965 proposed an equation called the universal equation of soil loss, since it considers all the factors that cause erosion. The Universal Soil Loss Equation (USLE) predicts the average long-term annual erosion rate in a sloping field based on the type of precipitation, the type of soil, the topography, and the cultivation system and management practices. The USLE is the most used empirical tool for predicting water erosion, as a result of a statistical analysis of >10,000-year-based data on runoff and ground loss. To define the mathematical structure of the USLE, a reference condition, called unit diagram, was used. The unit plot was defined as a plot of 22.1 m length, with a 9% gradient, constantly maintained in a normal condition plowing agriculture force slope up and down. It was found that the model was a logical structure with respect to the variables used to simulate the soil erosion processes in the plot scale (Ferro 2010). The USLE was conceived as an instrument to support management decision to estimate the average erosion rate over a long period of time (~20 years), ignoring how individual events contribute to the average annual value and neglecting the dominance of relatively rare events in the determination of long-term erosion averages (González-Hidalgo et al. 2010, 2012; Larson et al. 1997; Meena and Yadav 2014). In USLE or RUSLE, there is no direct consideration of runoff even if, for a given event, the loss of soil per unit area, Ae (ML^{-2}), is given by the product of the amount of the outflow, Qe ($L^3 L^{-2}$), and bulk sediment concentration, Ce (ML^{-3}). Kinnell and Risse et al. (1998) noted that for outflow plots and loss of soil used to develop the USLE, the sediment concentration for individual events depended on event precipitation erosivity event, EI_{30} (Wischmeier and Smith 1978) per unit precipitation, Pe and so-called developed USLE-M model, using the term

Qe EI_{30}/Pe = Q_R EI_{30} as the erosivity index being Q_R event outflow coefficient (Kinnell and Risse 1998; Kinnell 2007, 2010). The Universal Equation of Loss of Soil (USLE) is similar to

$$A = R.K.L.S.C.P$$

where

A = Average annual soil loss in $tacre^{-1}$ (tons per acre)
R = Rainfall erosivity index
K = Soil erodibility factor
LS = Topographic factor; L is for slope length and S is for slope
C = Cropping factor
P = Conservation practice factor

R = Rainfall erosivity. It is a measure of rainfall energy and intensity rather than just rainfall amount. The product of kinetic energy and 30-minute maximum rainfall intensity is termed as rainfall erosivity or EI.

K = The soil erodibility factor. It is a measure of the relative resistance of a soil to detachment and transport by water. The soil erodibility factor is determined by considering the soil loss from continuous cultivated fallow land without the influence of crop cover.

LS = The slope length and steepness factor. Length and slope factors are combined together and are called topographic factor. It is the expected ratio of soil loss from a given field slope to that from a slope 22 m in length with a uniform slope of 9%. Slope (L) is measured from the point of origin of overland flow to the point where deposition begins and/or where the water enters a defined channel. Slope is directly proportional to soil erosion.

C = The crop and management factor. It is the ratio of soil loss from land cropped under specified conditions to the corresponding loss from clean-tilled, continuous fallow.

P = The support practice factor. It is the ratio of soil loss with a specific support practice to the corresponding soil loss with up-and-down hill culture. The conservation practice consists of mainly contouring, terracing, and strip cropping.

The values of erodibility factor K for use in USLE for different soils of India have been determined based on runoff plot studies, reported by Snaydon and Harris (1981); these are cited in Table 3.9.

Table 3.9 Values of erodibility factor K for use in USLE for different soils of India

Soil type	Station	K
Loamy sand, alluvial	Agra	0.07
Dhulkot silt loam	Dehradun	0.15
Red chalka sandy loam	Hyderabad	0.08
Soil from laterite rock	Kharagpur	0.04
Kota clay loam	Kota	0.11
Laterite	Ootacamund	0.04
Sandy loam, alluvium	Vasad	0.23

The Universal Soil Loss Equation predicts the soil loss irrespective of slope, soil type, slope length, and cropping pattern. It helps in selection of the agricultural practices and provides recommendations on crop management practices to be used. However, Universal Soil Loss Equation does not compute sediment deposition. To avoid limitations of Universal Soil Loss Equation later on, RUSLE and MUSLE were proposed (Suresh 2012). A quantitative assessment of average annual soil loss for Micro-watershed 1E1C4a2 is made with GIS based well-known RUSLE equation yields maximum soil loss of 2.9246 t h-1 y-1 with a close relation to grass land areas and agricultural lands (Bhat et al. 2017). Kumar et al. (2016) conducted a study to predict the soil loss using USLE equation in the khimbar micro-watershed of Kashmir valley. The study estimated average soil loss of 14 t h-1 y-1 and total soil loss of 59077.2 t y-1 in entire the micro watershed.

3.12 Soil Sustainability for Future Generation

Sustainability means meeting our needs without compromising the ability of the future generation to meet their needs. Soil erosion control is necessary for soil sustainability. If the soil degrades, crop yield will not be sufficient to meet our needs. Sustainable soil is necessary for sustainable agriculture. According to Wendell Berry, sustainable agriculture does not exhaust the soil or people. Healthy soil is a key component in sustainable agriculture. Healthy soil together with water and nutrients produces healthy crops that are less susceptible to disease. Soil must be protected to ensure long-term productivity and stability. The methods of protection include all the factors discussed in this chapter. For soil sustainability, it is necessary to use biological fertilizers instead of chemical fertilizers that influence the soil. Biochar should be used as it increases crops and sustainability in poor soils. Organic farming must be practical, as it builds healthy soils by feeding the microbial inhabitants that release, transform, and transfer nutrients. Organic farming promotes healthy soils rich in micronutrients and that can be used for decades to grow without exhaustion. In summary, to achieve sustainable agriculture, soil sustainability is essential and can be achieved through appropriate soil conservation methods, using improved seed varieties to enhance yield under better cultivation practices. Organic farming can be also one of the alternatives for sustainable crop yield improvement. Besides this mixed cultivation, crop rotation, and use of legume crops, using appropriate harvest models for crop rotation and use of vermicompost can have a drastic impact on our already burdened agriculture sector.

3.13 Conclusions and Future Perspective

The reductionist research has undoubtedly provided a great deal of information and an excellent understanding of many fundamental soil properties and processes that are affected and influence many land management decisions. We suggest, however, that in isolation, a reductionist approach does not provide answers to complex questions such as the interaction of increasingly fluctuating weather patterns, variable landscapes and different cultivation systems, or which soil and crop management strategies should be regulated in response to these and other factors to provide food, fibers, and fuel needed to support more than nine billion people. Field research results are often strongly influenced by climatic and landscape properties (especially those affecting soil moisture content). A probability surface describing the occurrence of critical environmental factors from a field study can be used to incorporate temporal variance in the spatial inference model of a study. These domains help identify areas of similarity where the survey results would likely be applicable. The use of new search approaches and visualization processes allows users to define inference areas they consider most relevant to their research or production environment. These techniques can also be used to guide future research, extend research results to end users, and help manufacturers manage risks. Nature has a lot to offer to the current challenges facing society and the world, but unfortunately, societies tend to ignore or resort to the offer/solution of nature as a last resort. Today, the world/humanity faces a lot of environmental problems. However, if researchers pay more attention to the study and understanding of nature and the positive laws of nature, it should help them play a fundamental role in overcoming and treating most of these problems.

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4

Conservation Agriculture: Perspectives on Soil and Environmental Management in Indo-Gangetic Plains of South Asia

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Abstract

Bread and rice basket of South Asia is feeding ~20% of the global population. The agricultural production system in South Asia is predominated by exhaustive cereal production system including rice, wheat, and maize. Thus, it greatly affects the livelihood and nutritional security of the rural and urban poor. Recently, cereal productivity had slowed down or stagnated. Present expansion rate in terms of yield of rice and wheat is ~2–3 times higher than in 1966–1994. During 1980s, the peak of “Green Revolution” in the agricultural production system helps in the reduction of rural and urban poverty by making food more affordable. During the 1990s, growth in yields slows down because of technological stagnation resulting in high food prices. Slow growth in yields mainly inflated on wheat and rice by ~1%. Therefore, agriculture in South Asia is presently in front of a major challenge of resource fatigue and declining crop productivity. In addition to that, a huge gap exists in yields mainly due to yield gap management, ranging from 14–47, 18–70, and 36–77% in wheat, rice, and maize, respectively. Crop residues are considered a vital natural resource for protecting and sustaining soil and crop productivity. Application of crop residues is useful for maintaining or enhancing soil organic matter (SOM). This chapter presents the perspectives on soil and environment through principles of conservation agriculture (CA) for sustainable cereal production system in Indo-Gangetic belts of South Asia.

Keywords
Carbon sequestration · Conservation agriculture · Crop rotation · Crop residue · Greenhouse gases · In situ mulching · South Asia · Water productivity

Abbreviations

BNF	Biological N fixation
CA	Conservation agriculture
CEC	Cation exchange capacity
CGIAR	Consortium of International Agricultural Research Centres
CIRAD	French Agricultural Research Centre for International Development
CRM	Crop residue management
CRR	Crop residue retention
CRs	Crop residues
DAP	Di-ammonium phosphate
DSR	Direct seeded rice
ET	Evapotranspiration
FAO	Food and Agriculture Organization
FUE	Fertilizer use efficiency
FYM	Farm yard manures
GHGs	Greenhouse gases
GIZ	German Agency for International Cooperation
HYVs	High-yielding varieties
IGPs	Indo-Gangetic plains
IPM	Integrated pest management
IWM	Integrated weed management
NARS	National Agricultural Research System
NGO	Non-governmental organization
NT	No-tillage
NUE	Nutrient use efficiency
OM	Organic matter
RCTs	Resource conservation technologies
RWCS	Rice-wheat cropping system
SMB	Soil microbial biomass
SOC	Soil organic carbon
SOM	Soil organic matter
TOC	Total organic carbon
VAM	Vesicular arbuscular mycorrhizae
WUE	Water use efficiency
ZT	Zero tillage

4.1 Introduction

Nowadays, a challenge is rising with quick growing prices of food and energy and diminishing natural resources, i.e., water, the liability of soil degradation, desertification, and losses in biodiversity (Kumar et al. 2014a, b, c; Ashoka et al. 2017). Thus, a lot of challenges lie ahead as the population of India in 2050 will be ~1.75 million and per capita availability of land will be ~0.09 ha (Kumar et al. 2018a, b, c, d, e, f, g, h, i, j, k). Intense threat of food and nutritional security that overwhelms the poor leading to augment paucity will intensify additional pressure on agriculture sector (Chatterjee et al. 2016). Conservation agriculture (CA)-based resource conservation technologies (RCTs) had proven to produce more at low cost, alleviate ecological imbalance, avoid residue burn, and improve soil health and advancing in timely sowing of winter crops to tackle issue of terminal heat stress at its reproductive stages (Samal et al. 2017; Kumar et al. 2018a, b, c, d, e, f, g, h, i, j, k). Agriculture feed and provide energy to the ever-increasing population and lower ecological unessential effect (Kumar and Kumawat 2014; Meena and Meena 2017). Rice-wheat cropping system (RWCS) occupies ~13.5 M ha in Indo-Gangetic plains (IGPs) of South Asia and feeds ~20% of the global population. It has a huge value for food and nutritional security in the Asian region (Ladha et al. 2009; Bohra and Kumar 2015; Yadav et al. 2018a). Wider adoption of high-yielding varieties (HYVs) of cereal beside better crop management, irrigation, and inorganic nutrients in "Green Revolution" had amazingly increased system productivity (Prakash et al. 2017). For more than a decade, cereal productivity had stuck in RWCS that failed to increase even ~1.0%, far behind population growth (Prasad et al. 2018; Kumar et al. 2018a, b, c, d, e, f, g, h, i, j, k). The productivity of RWCS is stagnant and total factor productivity is declined owing to exhausted natural resources. Thus, the sustainability of this system is a threat (Saharawat et al. 2010; Kumar et al. 2018a, b, c, d, e, f, g, h, i, j, k; Erenstein et al. 2008). Therefore, food and nutritional securities are moving toward endangerment, and the challenge of the post "Green Revolution" agriculture poses an extra hindrance (Kumar et al. 2018a, b, c, d, e, f, g, h, i, j, k). Increased yield and monetary returns are difficult to attain by sole-centric approaches. Therefore, a system approach is essential to augment the production of rice and wheat in system modes in Indo-Gangetic plains (IGPs) (Kumar et al. 2008a, b; Saharawat et al. 2009; Yadav et al. 2018a, b, c). Conventional RWCS is mostly inputted exhaustive, and therefore, suitable alternatives are immediately required to replace it (Kumar et al. 2018a, b, c, d, e, f, g, h, i, j, k). In the current view, numerous innovative strategies were tested that ascertain high returns and lower drudgery and input cost and offer better ecological security. The probable solution includes positive changes from a conservative production system to RCTs, i.e., laser land leveling, no-till (NT), and direct seeded rice (DSR) (Kumar et al. 2015a). Novel participatory research model involving farmers, researchers, inputs, machine suppliers, and extension workers as a team was adopted for spreading of RCTs. Introduction of RCTs in this region is mostly driven through cost-effective approaches, reduced tillage, and NT, thereby reducing the cost of cultivation and permitting better suitability in crop planting (Deumlich et al. 2006). Adoption of

CA in IGPs of South Asia is still weak compared to other parts of the globe (Derpsch 2005). Thus, there is immediate attention for the farmers that prefer a CA because of the lower cost of cultivation and its ability to sustain the system productivity in longer perspectives. It is not obvious whether this benefit alone will go ahead to the wider adoption of CA. Thus, to address these issues of resource exhaustion and bridging the gap management in yields, CA-based management solution is keystone (Kumar et al. 2013a, b; Kumari et al. 2014; Kumawat et al. 2015; Sofi et al. 2018). In this chapter, the perspectives of soil and environmental management under cereal production system in IGPs of South Asia are nicely discussed.

4.2 Historical Expansion of CA

Tillage, mainly in a delicate ecosystem, was a matter in the early 1930s, while dust bowl weighed down a large area of the USA. The concept of minimum tillage and retaining the soil cover came up, and the word CA was begun for soil management. Planting machinery development was permitted in the 1940s to perform sowing in straight line exclusive soil tillage. The hypothetical concept of CA was introduced by Edward Faulkner in his book *Ploughman's Folly* (Faulkner 1945) and Masanobu Fukuoka in *One-Straw Revolution* (Fukuoka 1975). It was pending since the 1960s for NT came in agricultural practices in the USA (Kassam et al. 2014a; Varma et al. 2017a). During the 1970s, NT entered Brazil, wherever farmers in concert with scientist tainted skill into the systems, which nowadays is known as CA. However, it acquired an additional 20 years in advance of CA to achieve a considerable adoption. This time farm equipment/agronomical practices in NT had urbanized to optimize performances of crop, machinery, and field operations. This development is outlying since the imagination of farmers and researchers was fabricated to improve a benefiting system. In the early 1990s, CA progressed exponentially, leading to revolt in agriculture in Southern Brazil, Argentina, and Paraguay to farming practices in the USA (Derpsch 2004). During 1990s, this progress paying attention more compared to other parts of the world including international research organizations such as Food and Agriculture Organization (FAO), World Bank, German Agency for International Cooperation (GIZ), French Agricultural Research Centre for International Development (CIRAD), and Consortium of International Agricultural Research Centres (CGIAR). Advancement of conservation and NT practices in agricultural concept, i.e., CA, lead to wider adoption together with industrialized countries, mostly Canada, USA, Australia, Spain, and Russia. Later CA practice was augmented and getting more attention globally (Jeet et al. 2012; Jat et al. 2014a, b; Meena et al. 2016a). Globally, total acreage in CA during 2008–2009 was 106 M ha (Kassam et al. 2009), which increased to 125 M ha during 2010–2011 (Friedrich et al. 2012). In 2013, this area was increased globally to ~157 M ha (Kassam et al. 2014b). CA is adapted on soil which varies from 90% sand (Australia) to 80% clay (Brazil). Under CA, there is no soil that is flat to crusting/sealing in tillage practices, as mulching avoids creation of crust. It is adapted on all farm sizes ranging from half to several hectares in China and 1000 ha in Argentina and Brazil. A major hurdle in the adoption of CA is acquaintance on expertise, approach, insufficient policy such as product-based subsidy on direct farm payment, unavailability of suitable machineries, and herbicide strategies particularly for a bigger farm in a developing country (Farooq and Siddique 2014; Kumari et al. 2010; Yadav et al. 2017b). This assisted recently by many international and national organizations, i.e., FAO, World Bank, CIRAD, CGIAR, and non-governmental organization (NGOs), which support CA for strengthening sustainable production and economic development. Therefore, long-term dispersion of CA worldwide needs efficient state and local policy and institutional supports (Kassam et al. 2014c; Kumar et al. 2015a; Dadhich and Meena 2014).

4.2.1 Worldwide Area and Distribution

Worldwide realistic evidence illustrates that farmer-led renovation of an agricultural production system based on CA principles is by now taking place and gathers impetus internationally for the twenty-first century as climate-smart agriculture. CA system encompasses reduced soil disturbances, organic mulches to cover soil, and diversification of cropping pattern in combination with the better practice of crop management. During 1973–1974, CA covers merely ~2.8 M ha globally, acreage during 1999 was 45 M ha, and during 2003, it was 72 M ha. Over the last 10 years, it extended to >8.3 M ha year^{-1}, while in 2008–2009, it was 10 M ha year^{-1}, showing improved attention of farmers nationwide (Table 4.1). Recent evidences showed that ~66.4 M ha of global area was under CA in South America (~60% of croplands), ~54 M ha in the USA and Canada (~24% of croplands), ~17.9 M ha in Australia and New Zealand (~36% of croplands), and ~10.6 M ha in Asia (~3% of croplands) (Fig. 4.2). In Asia, the adoption of CA has been improved significantly during the last 10–15 years. Acreage in CA had increased ~3-fold during 2008–2009 (2.7 M ha) to 2013 (10.3 M ha) (Fig. 4.1). In Central Asia, a rapid expansion of CA had been noted in recent 5 years (Figs. 4.2 and 4.3). Presently, there is ~6.7 M ha in China and 23,000 ha in Korea under CA. In IGPs, Pakistan, Nepal, and Bangladesh under RWCS, there is a huge adoption of NT wheat (5 M ha). During the last 10 years, CA has expanded to 10 M ha/year. The main reason for the adoption of CA is to gain more attention and support from the government, international agencies, NGOs, and service sectors during the last decades.

4.2.2 Sketch of CA

The principle of CA is a unanimously appropriate use of agricultural land by means of local invented and modified practices (Kumar 2015a, b). Soil intervention, i.e., mechanical tillage abridged to complete minimum tillage or avoiding the use of external input like agrochemicals, crop nutrition is applied in optimum quantities that have no interference with a biological process. CA facilitates better agronomical approaches, such as appropriate farm operation, improving the whole cropping

Table 4.1 Worldwide adoption of CA (Kassam et al. 2015)

Country	CA area '000 ha 2013 update	Country	CA area '000 ha 2013 update
USA	3561	Turkey	45
Brazil	31811	Mexico	41
Argentina	291810	Moldova	40
Canada	18313	Slovakia	35
Australia	17695	Kenya	33.1
China	6670	Portugal	32
Russia	4500	Ghana	30
Paraguay	3000	Syria	30
Kazakhstan	2000	Tanzania	25
India	1500	Greece	24
Uruguay	1072	DPR Korea	23
Spain	792	Switzerland	17
Bolivia	706	Iraq	15
Ukraine	700	Sudan	10
Italy	380	Tunisia	8
South Africa	368	Madagascar	6
Zimbabwe	332	Hungary	5
Venezuela	300	Morocco	4
Finland	200	Uzbekistan	2.45
France	200	Lesotho	2
Zambia	200	Azerbaijan	1.3
Germany	200	Lebanon	1.2
Chile	180	Kyrgyzstan	0.7
New Zealand	162	Netherlands	0.5
Mozambique	152	Namibia	0.34
United Kingdom	150	Belgium	0.27
Colombia	127	Ireland	0.2
Malawi	65		

husbandry in the rainfed and irrigated ecosystem (Jat et al. 2014a, b; Meena et al. 2015d). Yield potential of CA is similar and even higher than that of the traditional system, which means CA does not have yield penalties. On the same moment, CA meets the terms by means of established thought of environmental sustainability (Kassam et al. 2013; Mitran et al. 2018). As a result, increased system diversity and encouraged soil biological activities owing to reduced erosion and leaching and other agrochemicals are cut down in longer perspectives (Kumar 2017). Water quality is enhanced due to a decrease in pollution from agrochemicals and erosions (Kumawat et al. 2012; Buragohain et al. 2017). It helps to sequester carbon in the soil at ~0.2–1.0 t ha^{-1} year^{-1} depending on locality and crop management (Corsi et al. 2014). It also saves labor and fuel saving by ~50 and 60%, respectively, to farmers (Friedrich et al. 2009; Crabtree 2010).

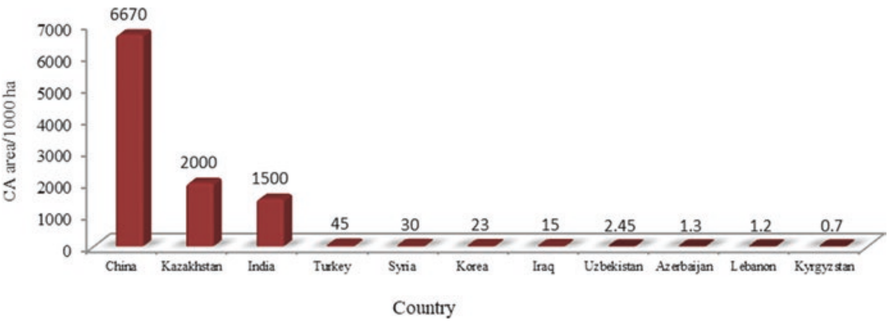

Fig. 4.1 Recent trends in adoptions of CA coverage in South Asia (Kassam et al. 2015)

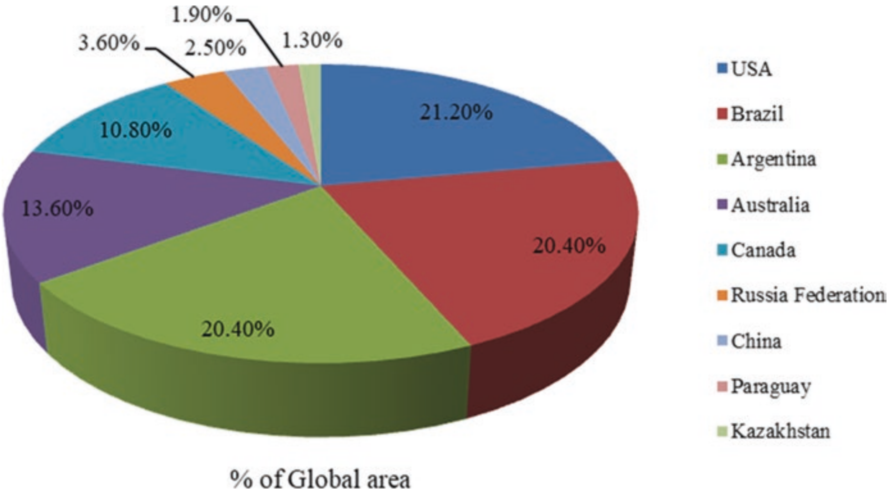

Fig. 4.2 Worldwide adoption rate (%) of CA (Kassam et al. 2015)

4.2.3 Call for Taking into View on Ecological Footprint of Agriculture

There seems to be no option other than to enhance production and factor productivity to meet global demand for food, feed, and fibers to reduce hunger and poverty (Kumar et al. 2017a, b, c, d, e, f, g, h, i, j, k). There is an urgent need to boost the elasticity of production system by eliminating biotic and abiotic stresses (Kumar et al. 2015a). Further, it is required to stop the degradation of cultivated land and over-exploitation of ecosystem services. However, crop intensification and

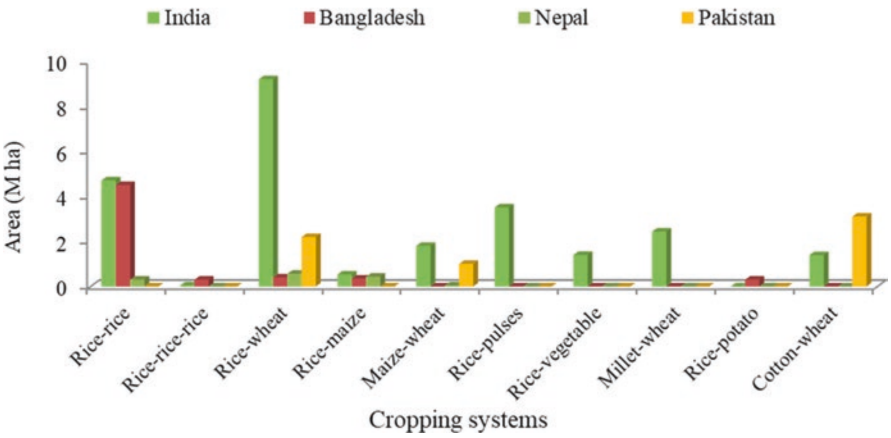

Fig. 4.3 Acreage in prevailing cropping systems in South Asia (Jat et al. 2010)

exhaustive tillage production system had incompatible effects on soil, water, and biodiversity services offered by nature (Kassam et al. 2013; Mishra and Kumar 2017a, b; Meena et al. 2014). These caused a decline in grain yield and factor productivity which compelled scientists to think about options which are more economically sustainable (Jat et al. 2014a, b; Meena and Lal 2018). The agricultural production system is responsible for ~30% of total greenhouse gas (GHG) emissions, i.e., CO2, N2O, and CH_4, though in a straight line inflated by climate change (IPCC 2014). Sustainable production and intensification must lower the impacts of climate change on crop production. A set of soil–crop–nutrient–water–landscape management practice has been recognized to achieve these goals (Kassam et al. 2013; Varma et al. 2017b). CA allocates energy and mineral N use in cultivation and thus cuts down GHG emission, improves soil biological activity, and improves yield and factor productivity in the long term (FAO 2011).

4.3 Cereal System in South Asia

Rice, wheat, and maize are the most important cereal crops grown as monocrops in rotation under the tropical/subtropical condition of South Asia (Jat et al. 2010; Meena et al. 2018a, b, c). In irrigated and rainfed lowland condition, rice-rice, rice-wheat, and rice-maize are major cropping system. Rice-rice system is common in South India which has a tropical climate (Kumar et al. 2009). RWCS is widespread in the subtropical condition of IGPs of Bangladesh, India, Nepal, and Pakistan, whereas rice-maize systems are prevailing in tropical/subtropical and warm temperate areas. There are mostly three major cropping seasons in South Asia (Kumar et al. 2014a, b, c; Meena et al. 2018b).

4.3.1 Production System Constraints and Natural Resource Management (NRM) Solutions

In the past, impressive gains in productivity of rice, wheat, and maize cropping system were mostly owing to overture of better-quality cultivars, intensive use of fertilizers, increase in irrigation, and interaction among all inputs (Kumawat et al. 2013a, b; Kumar 2015c; Kumar et al. 2015a,b, c; Datta et al. 2017a). Natural resource management problems are habitually complex in nature and require a site-defined solution. A series of stakeholder consultations in NW and Eastern IGPs were organized, and then production system constraints were identified, which limit the productivity of cereal. These can be tackled through the adoption of suitable technologies.

4.3.2 Strategic Points for Improving the Productivity of Cereal-Based System

IGPs of South Asia are a relatively homogenous agro-eco region, mostly with cereal-dependent system with rice, wheat, and maize. However, the relative strength of National Agricultural Research System (NARS) situated in various parts of India, the right use of infrastructure, farm energy, socioeconomic status of farmers, and susceptibility to climatic abrasion differ extensively in N-W and Eastern IGPs (Kumar et al. 2017a, b, c, d, e, f, g, h, i, j, k; Dhakal et al. 2015). Livestock is a vital asset in delicate ecologies prone to chronic flood in E-IGPs. Increased biomass production in such ecologies holds the key for the survival of rural masses. To manage long-term soil fertility, productivity, as well as environmental quality, important strategic points are considered:

- Integration of organic and inorganic fertilizer can be the most sustainable practice to adopt.
- Optimizing nutrient inputs by taking all possible nutrient sources into consideration
- Matching nutrient supply in root zone with crop requirements spatially and temporally
- Reducing N losses in intensively managed cropping systems
- To integrate soil and nutrient management with high-yielding cultivation system
- Use of new tools in genomics, transgenics, and phenomics for improving cereal crop yields

4.3.3 CA Principles and Practices

Conservation agriculture is a concept for optimizing crop yields, economics, as well as ecological issues. The key element of CA includes NT, retentions of CRs on the soil surface, novel cropping system, and measures to reduce compaction during forced traffic. This must be evaded if zero tillage (ZT) is to be practiced for a long run (Kumar et al. 2017a, b, c, d, e, f, g, h, i, j, k). These CA ideologies are not location-defined although invariable goal that is proficient to expand CA transversely in all production. CA system is not only merely on precise sowing with seed drillers and no-tillage (Kumar et al. 2018a, b, c, d, e, f, g, h, i, j, k), but also management practices of weeds, water, nutrient, and integrated pest management (IPM), so as to formulate ZT (Mishra et al. 2017; Kumar et al. 2018a, b, c, d, e, f, g, h, i, j, k; Yadav et al. 2017c). These merely suggested that CA is dividable in nature and elastic in operations and permitted farmers to profit from them in varied condition (Mandal et al. 2011a). CA then would be capable of quick tackling the vital need of South Asia nowadays in a climate change scenario.

4.3.4 CA-Based Crop Management: A Shift in Idea

Still, the majority of agronomic work turns around tillage (Roy et al. 2011). Deteriorating status of soil organic carbon (SOC) had major shifting in agriculture from “conventional animal-based survival” to “rigorous inorganic and traction-based” agriculture so as to a problem related to the sustainability of the natural resource. In India, SOC content of cultivated soil is <5 g kg^{-1} as compared to 15–20 g kg^{-1} in untilled virgin soil (Kumar et al. 2016a, b, c, d). Lower SOC content was credited to plowing, removals of CRs, and depleting soil fertility (Lal 2004). The large part of cultivated land shows fertility exhaustion and lack of micro-nutrient under RWCS (Kumar et al. 2017a, b, c, d, e, f, g, h, i, j, k; Meena et al. 2016b). it acquired a few decades to shift from the common belief that the following summer was only meant to get better productivity and confidence that abridged ZT benefit (Kumar et al. 2017a, b, c, d, e, f, g, h, i, j, k). CA is extensively established as the main component for improving productivity and ecological excellence and conserves natural resource for food safety and poverty mitigation (Paswan et al. 2017a, b; Kassam and Friedrich 2009; Kumar et al. 2016a, b, c, d, e, f, g, h, i, j, k, l, m, n). No-tillage (NT) is considered as an innovative step in the way of avoiding land degradation (Sarkar et al. 2016, 2017; Yadav et al. 2018a). NT in combination with related management practices, i.e., direct sowing in CRs to provide soil covers to conserve moistures, sensible crop rotations, and agroforestry system, comprises CA (Mandal et al. 2011b; Kumar et al. 2017a, b, c, d, e, f, g, h, i, j, k; Layek et al. 2018). CA is an innovative process of just beginning of suitable CA implement, cultivar for guidance, and well tunes for changing in crop productions (Kumar et al. 2017a, b, c, d, e, f, g, h, i, j, k; Kumar et al. 2018a, b, c). CA practices abridged tillage variation in tropics and temperate region to grow upland cereal system (Singh et al. 2017a, b). CA has progressively inflated globally to cover ~7% of globally total cultivated lands (FAO 2016). It has to be considered that conservation tillage (CT) and CA are not the same.

4.4 CA in IGPs of South Asia

India has achieved a record food grain production of ~275.1 MT in 2016–2017, and hence, crop residues (CRs), a by-product of the crop production system, have increased proportionately (Chand et al. 2017). Total removal of plant nutrients by different crops is significantly higher than addition through fertilizer nutrients in India, resulting in continuous depletion of soil fertility (Kumar et al. 2017a, b, c, d, e, f, g, h, i, j, k; Sihag et al. 2015). Indian soils are generally low in SOM with poor soil fertility (Kuotsuo et al. 2014). Such a scenario is leading to widespread and acute multiple nutrient deficiencies in the soil in a cereal production system. Rice-wheat, rice-rice, pearl millet-wheat, soybean-wheat, maize-wheat, cotton-wheat, and rice-maize are the most important cereal systems of India. Among these, rice-wheat occupies an area of over 10 M ha spread over IGPs, followed by rice-rice (5.89 M ha), pearl millet-wheat (2.25 M ha), soybean-wheat (2.23 M ha), maize-wheat (1.86 M ha), cotton-wheat (1.50 M ha), and rice-maize (0.7 M ha) (Fig. 4.3). About one-third of the total cereal production of India comes from IGPs. Two states, i.e., Punjab and Haryana in India currently representing a highly productive RWCS in IGPs, contribute ~69% of total food grains of the country (84% wheat and 54% rice) and are known as the food bowl of India. Low levels of SOM, emergence of multi-nutrient deficiency owing to their excess mining from soil, and non-recycling of CRs are main reasons for declined productivity, particularly in RWCS (Meena et al. 2011a; Kumawat et al. 2013a, b; Kumar and Deka 2016; Kumar et al. 2016a, b, c, d, e; Zeliang et al. 2018). Continuous removing/burning of residue leads to decline in soil fertility which results in the application of fertilizer at higher rate, eventually leading to high input in short term and reduced soil productivity in the long run (Kumawat et al. 2017a, b, c). Retaining CRs on soil surface would improve nutrient cycling and soil and environmental properties (Kumar and Kumar 2015; Kumar et al. 2016f, g). Adoption of CA principles together with best management practices (BMPs) would improve the productivity and resource use efficiency and would result in greater prosperity over a time.

4.4.1 Availability of Crop Residues in India

It is apparent that the total production of CRs is 686 MT (Table 4.2) in India, yearly produced by 26 crops (Hiloidhari et al. 2014). Residues to economic yield ratio for cereal crop vary from 1.3 for wheat, 1.4 for rice, 1.5 for oat and barley, and 2.0 for maize. Out of total CRs produced in India, cereals (rice, wheat, maize, pearl millet, barley, small millets/sorghum) contribute a maximum of 368 MT (54%) followed by sugarcane 111 MT (16%). Among crops, paddy adds the highest of 154 MT of total residues compared to wheat (131 MT). Gross residue potential is a full quantity of residues produced, whereas extra residue potential is residues left subsequent to rival uses. Considering the extra portion of CRs accessible from chosen crop, the national potential is ~234 MT year^{-1}, and 34% of total residues produced in India are on hand (Fig. 4.4). Cereal contributes a maximum of surplus residues (89 MT)

Table 4.2 State-wise surplus crop residue potential in India (Hiloidhari et al. 2014)

Group	Crop	N	P	K
Cereals	Corn	39	3	19
	Oat	55	8	58
	Spring barley	43	7	40
	Triticale	54	8	28
	Winter rye	45	8	24
	Winter wheat	53	9	42
Legumes	Pea	112	14	74
	Soybean	132	14	72
Oilseeds	Mustard	91	21	127
	Poppy	115	24	204
	Sunflower	108	15	218
	Winter rape	107	22	157
Forage crops	Alfalfa	126	21	66
	Clover	127	17	66
	Silage maize	55	4	26

than sugarcane (56 MT). Though paddy produced maximum gross residues among crops, its excess residues produced are lesser than sugarcane. This might be due to the fact that paddy residue has additional uses (cattle feeds, animal feeds, packing materials, food preparation) compared to sugarcane. Among states, Uttar Pradesh generates the maximum CRs in the country, having a surplus of 33% (Shivran et al. 2013). A huge quantity of CRs is available either for retaining in the field to enhance productivity and soil fertility or removing from the field for alternative use, but in South Asia, CRs produced in RWCS have been considered a nuisance by farmers and disposed of through burning in fields (Ray et al. 2016a; Kumar et al. 2016h, i, j; Kumar and Meena 2016; Mishra et al. 2016; Kumawat et al. 2017a, b, c; Meena and Yadav 2015).

4.4.2 Challenges of Crop Residue in India

Cereal residues are widely used as cattle feed and animal bedding, while fuel for cooking and heating, composting, and housing material (Kumar et al. 2015a, 2016d, e; Ray et al. 2016b). Use of CRs is not consistent among different regions in India (Kumar et al. 2014a, b, c, 2017g, h, i, j). In some parts of India, wherever forest resources are not enough, people exploit residues simply as energy sources for cooking (Kumar et al. 2016a, b, c, d, e, f, g, h, i, j, k, l, m, n; Kumawat et al. 2016a, b; Gogoi et al. 2018). However, paddy straw is not desired as cattle feeds in Punjab, Haryana, and Western UP due to its high Si content of 12–16% vs 3–5% in wheat straw (Singh et al. 2015). Paddy straw is more palatable than leaves as their Si contents are low; thus, paddy may be harvested adjacent to the ground if possible if straw is to be fed to the livestock.

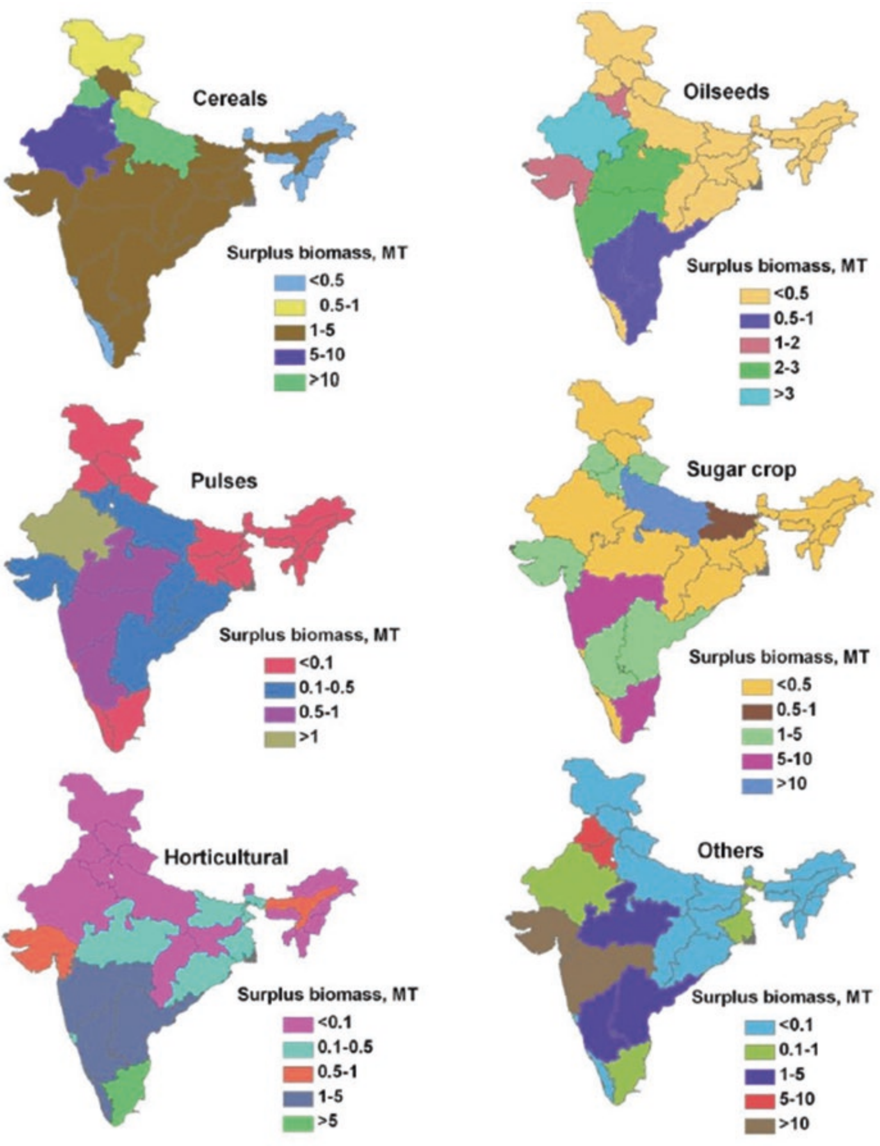

Fig. 4.4 State-wise surplus crop residue potential in India (Hiloidhari et al. 2014)

4.4.3 Crop Residue as Source of Plant Organic Nutrient

Crop residues are an excellent source of plant nutrient and organic matter as they constitute C >40% of dry matter and represent a vital component for the agricultural production system. About 30–40% N, 25–35% P, 70–85% K, and 35–45% S absorbed by cereal remain in vegetative part at harvesting. Usually, nutrient contents in paddy straw (per tonne) at harvesting are 5–8 kg N, 0.7–1.2 kg P, 15–25 kg K, 0.5–1 kg S, and 3–4 kg Ca on a dry weight basis. Rice straw contains~50–100% higher K concentration than wheat straw. Similarly, maize stover contains more N and K than wheat straw. In addition to NPK, 1.0 t of paddy/wheat residue contains ~9–11 kg S, 100 g Zn, 777 g Fe, and 745 g Mn. Nutrient content in CRs depends on soil, management practices, cultivars, and growing season. The quantity of NPK content in rice/wheat residue formed (197 T) is 4.1 × 106 t in India. Elimination of residues for off-farm purposes apart from composting and as fodders had a negative effect on nutrient supplies on behalf of economic loss and would have a harmful effect on soil, water quality, and overall sustainability of agricultural system in long term (Singh et al. 2008). The efficiency of nutrient uptake by crops from fertilizers/CR release is to be similar to 30–50%.

4.4.4 In Situ Burning of Crop Residues

Rising constraints of labors and time in extensive agriculture system lead to the implementation of mechanization in the RWCS system and leave a huge quantity of CRs in the field. Residues obstruct in tillage and planting of succeeding crop. Farmers in NW India and many parts of Eastern and Southern India often prefer to burn surplus CRs to establish next crops. Out of 89 MT of surplus cereal residues, rice and wheat constitute ~85%, which are burned on farm annually. Of total CRs burned globally, India contributes ~33.6%. In Punjab alone, ~20 MT of paddy and wheat residues out of whole 37 MT of residues are burned in situ every year, which leads to loss of ~8 MT of C equivalents to CO2 load of ~29 MT/year and also loss of ~1 × 105 ton of N, besides thrashing of S and annihilation of favorable soil microflora (Choudhary et al. 2013; Bhanwaria et al. 2013; Kumar et al. 2013a, b, Singh et al. 2015; Kumar and Deka 2017). Due to the burning of CRs, there is incidence of harmful effect on human/animals' health and road accident because of invisibility in NW India (Singh et al. 2010b). 1.0 ton of CRs on burning liberates 1515 kg CO2, 92 kg CO, 3.83 kg NOx, 0.4 kg SO2, 2.7 kg CH_4, and 15.7 kg non-methanogenic compound (Andreae and Merlet 2001). These gases and aerosols consist of carbonic matters that have adverse impact on human health and act as the main source of climatic change. Estimated open field burning of CRs is ~25% of available residues. It is estimated that the emissions from field flaming of paddy/wheat straw in India were 110 Gg CH_4, 2306 Gg CO, 2.3 Gg N2O, and 84 Gg NOx during 2000 (Gupta et al. 2004). Besides, burning of CRs leads to loss of organic matter and 80% of N and S, 10–20% of other nutrients. Many state governments in India have made the burning of CRs illegal. However, it is very hard to impose these laws.

Fig. 4.5 Direct drilling of wheat into rice stubble

4.4.5 Option for Managing Crop Residues

Bulks of paddy/wheat in NW India and other regions are harvested by the combined harvester, and much of residues are left in the field (Fig. 4.5). ~75% of wheat straw is used as feed for the animals by cutting machines, although this involves additional operation cost to the farmers (Kumari et al. 2013; Singh et al. 2014; Meena et al. 2015e).

Options available to the farmers for CRM includes burning, baling used as feeds or bedcovers for the animal, in situ incorporation in soil by means of tillage, and inclusive or incomplete retention on the surface as mulches with NT. After baling, CRs can be utilized for paper and ethanol production (Kumar and Deka 2017; Kumar et al. 2015d, e, f, 2018a, b, c, d, e, f, g, h, i, j, k).

4.4.6 Measures for Crop Residue Management (CRM)

For implementing sound decisions about CRM, it is essential to realize logically diminutive and importance of diverse CRM and to develop CRM technologies providing agronomic benefit in a cost-effective and environmentally acceptable manner (Saurabh et al. 2018b; Mishra et al. 2018). Singh et al. (2008) suggested that CRM options should be evaluated using criterion of productivity, ecological impact, and sustainability issues for the cropping system. The criteria of productivity of cropping systems are directly relevant to farmer's decision making (Kumar et al. 2017a, b, c, d, e). Quantifiable indicators of short-term productivity (1–3 seasons) include grain yield, fertilizer use efficiency (FUE), water use efficiency (WUE), and yield loss due to disease, insects, or weed pressure. Profitability indicators include income from yield with fewer inputs, i.e., labor, fertilizer, seed, machinery, irrigation water, and pesticides. CRM options can differ in their effects on indicators of productivity (Kumawat et al. 2009a, b, c; Jeet et al. 2010a, b, c; Kumar et al. 2010). Environmental impact and sustainability are criteria that are not typically important determinant for farmers in the selection of CRM option, but these criteria can be important for policy making, i.e., with the ban of open-field burning of CRs. The main short-term environmental impact associated with CRM includes changes in air quality and GHG emission (Meena et al. 2011a, b; Singh et al. 2011b, c; Verma et al. 2015a).

4.4.6.1 In Situ Incorporation of Crop Residues

The soil incorporation of CRs is useful in recycling nutrient and leads to momentary immobilization of N; higher C:N ratios could be corrected through application of additional N fertilizers at the time of residue incorporation (Singh et al. 2008, Kumar et al. 2018a, b, c). Crops are grown just after incorporation of residue suffers from N deficiencies due to microbial immobilization of N in the soil system. Period of net N immobilization and supplying of N from CRs to succeeding crop depends on the decaying period before sowing of next crops, residue quality, and soil ecological condition. Crop yield decreased with the incorporation of cereal residues instantly before sowing of succeeding crop over residue removal (Beri et al. 1995). Paddy straw can be managed in situ by means of permitting enough timing (10–20 day) in the midst of its incorporations and planting of wheat to avoid N deficiency that occurred due to N immobilization (Singh et al. 2004; Yadav et al. 2017a). Incorporation of paddy residues in the soil prior to wheat planting is tough for farmers because of the short interval between paddy harvesting and wheat sowing. The practice of paddy residue incorporation prior to wheat planting can be delayed by 2–3 weeks. Prasad et al. (1999) reported that paddy/wheat residue can be incorporated without harmful effect on crop under RWCS. Incorporation of paddy residue in soil had little effect on the yield of succeeding wheat crop over short term of <5 years (Singh et al. 2005). Many farmers in N-W states of IGPs collect wheat straw using straw combine after harvest for its use for animal feeding, although 20–25% (1.5–2.0 t ha^{-1}) remains in fields. Farmers even burn this small amount of residue prior to land preparation for paddy transplanting. They have uncertainty that wheat stubble would badly affect paddy crop. A field study conducted at PAU, Ludhiana, did not find any adverse effects of incorporating 2–3 t ha^{-1} of wheat residue on the subsequent rice yield. In middle and lower IGPs, the lower amount (1–2 t ha^{-1}) of the combine or manually harvested wheat straw/stubbles can be incorporated in the rice field before planting. Fallow periods of ~60–65 days after wheat harvesting can be used for raising pre-rice sole green-manuring or dual purpose pulses like mung bean for grain and green manuring. Sharma and Prasad (2008) noticed that combined application of wheat straw (high C:N ratio) through Sesbania green manure or mung bean residues (low C:N ratios) improved yields and N efficiency in rice.

4.4.6.2 Crop Residue Decomposition and Nutrient Release

Decomposition of CRs releases nutrients; they contain a mineral nutrient pool and carbon as CO2. The process of decomposition as well as N mineralization is controlled by the interaction of three components such as soil microorganisms/biological process, quality of CRs, and soil physicochemical properties. Combinations of this component not only decide the rate of decomposition of CRs but also the end product of the decomposition process. According to Sarkar et al. (1999), RWCS accounts for nearly one-fourth of the total CR production in India. One ton of rice residues contains ~ 6.1 kg N, 0.8 kg P, and 11.4 kg K, while one ton of wheat residues contain ~4.8 kg N, 0.7 kg P, and 9.8 kg K. Thus, proper CRM can play an important role in increasing SOM and nutrient supplying capacity, reducing ill effects of residue burning, as this leads to the destruction of SOM as well as plant nutrients, i.e., NPKS (Mandal et al. 2004; Kakraliya et al. 2018). Decomposition and nutrient release patterns of maize stover and rice straw were investigated under field condition in humid tropics, using litterbags of three mesh sizes (0.5, 2, and 7 mm), which allowed differential access of soil fauna. The nutrient release rate was increased with increasing mesh size of litterbags, suggesting that soil faunal activities enhanced nutrient mobilization.

4.4.7 Factors Affecting Residue Decomposition

Effective CRM depends on an understanding of factors influencing decomposition of CRs through microorganism and soil environment. Most of these factors are not self-regulating as a modification in one may affect changes in others. For example, higher soil moistures resulted in lowered soil temperature/aeration, and surface-residue placement may possibly affect soil moisture and temperature at the same time.

4.4.7.1 Crop Residue Quality

Plant residue contains ~15–60% cellulose, 10–30% hemicellulose, 5–30% lignin, 2–15% protein, and soluble substances (sugars, amino acids, and amino sugars and organic acids) that might constitute ~10% of total dry weight. Cutin, polyphenols, and silica are found in plants but differ depending on the species. The content of polyphenol generally increases with the age of CRs and is found greater in mature residues than in green plant. The process of CR breakdown depends on relative quantities of these fractions. CRs of cereal generally contain ~40% C on basis of dry weight, but their N concentration may vary greatly causing variation in C:N ratios. In most cases, cereal straw has C:N ratios of 80–100:1. C:N ratio is mainly imperative with regard to rate of CR breakdown if ratio of C:N is >20:1; the breakdown would be comparatively slower as soil microorganisms use N during the entire breakdown processes (Neupane et al. 2011a, b, c) (Fig. 4.6). To check a probable N deficiency, while adding residue with C:N ratio more than 20:1, N should be added to organic material or to the soil when the residue is included. C:N ratio of CRs may be helpful to envisage decomposition rates (Kumar et al. 2016a, b, c, d, e, f, g, h, i, j, k, l, m, n; Meena and Yadav 2014). Wide C:N ratio favors N immobilization, and narrower ratio favors mineralization (Gilmour et al. 1998). Lignin, hemicellulose, and polyphenol contents should also be measured for prediction of residue decomposition. Lignin is recognized as a recalcitrant fraction and extremely resistant to microbial decomposition, and decay rates of residues are inversely linked to lignin content (Fig. 4.6). Polyphenol content in plant tissues decreases the rate of

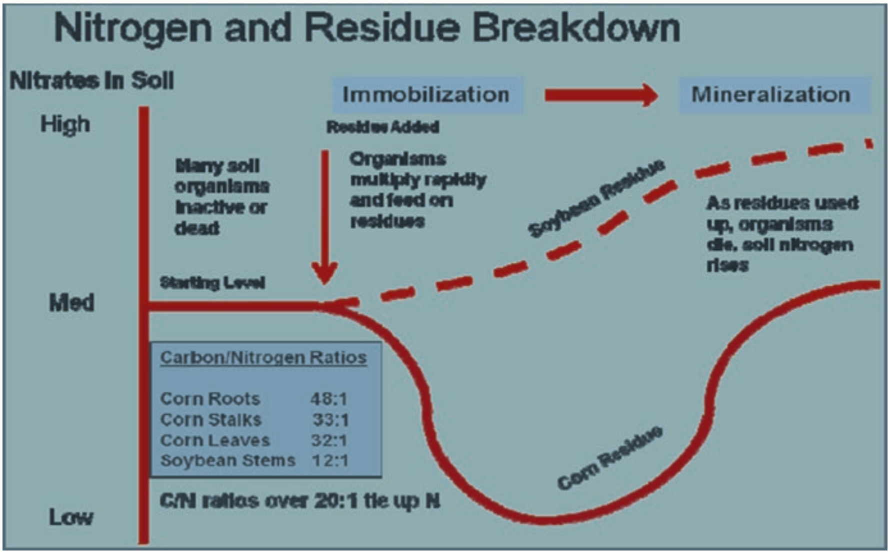

Fig. 4.6 Interaction between available N and microbes' activities in decay of CRs (Anon. 2016)

decomposition through bindings to proteins. The decomposition rate of CRs cannot be expected as of sole properties of organic materials. Polyphenols:N and lignin + polyphenol:N ratio is associated with residue decomposition and nutrient release. It had been recommended that lignin + polyphenol: N ratio could serve as an immediate index for cereal residue decomposition.

It was implicit that better accessibility of N was liable for higher decaying rate for wheat straw.

4.4.7.2 Environmental Factors

Temperature and rainfall are the main climatic factors that influence organic matter decomposition infield situation. Warm and humid climate provides a favorable environment for rapid residue decomposition (Singh et al. 2017a, b, c, d). Growth and activity of microorganism are maximum in the temperature range of 20–40 °C and thus support maximum residue decomposition within range. Soil water content can severely influence CR decomposition and nutrient recycling (Paswan et al. 2012; Yadav et al. 2013). Optimal soil water potential for residue decomposition is generally -0.03 M Pa or 60% of WHC. The lower rate of CR decaying in lowland situation is possible because of restricted aerations for microbial activities.

4.4.7.3 Management Factors

Huge quantities of CRs are generated in India by different cropping system whose management is quite problematic. CRs can be managed based on their type and their quantity being retained or incorporated into the soil. Residue position may be vital for calculating the rate of decomposition and nutrient recycling. Fast decomposition occurs in case of incorporated CRs compared to that of surface-retained residue because of better soil-residue contact, further favorable micro-environment mainly moisture regimes. Singh et al. (2010a) reported that incorporated paddy residues lost 80% of their original biomass by the end of decomposition cycle (140 days), at the decaying rate of 0.21–0.24 day^{-1} that was three times faster than surface placed residues (0.078 day^{-1}). About 50–55% of paddy residues placed at the surface were not decayed at wheat harvest. The entire N release from covered residue at the tillering stage was ~6 kg N ha^{-1} (15% of initial) on sandy loam and 12 kg N ha^{-1} (27% of initial) in silt loam (Singh et al. 2010a). The quantity of N released from covered residue on sandy loam improved to 12 kg ha^{-1} at booting stage. Rice/wheat residue is enriched in K and liberates 70% K within 10 days after its incorporation. Ease of CRs to soil microbes is the main factor influencing the rate of decomposition. The particle size of CRs provides a diverse degree of convenience that consecutively affects residue decomposition rate and the process of mineralization-immobilization. Normally, smaller particles decayed earlier than bigger particles as improved surface area and better distributions in soil would increase vulnerability to microbial activities. Angers and Recous (1997) reported the faster decomposition (3–17 day) in case of the minute particle (0.06–0.1 cm) than bigger sized particles (5 and 10 cm). After 102 days, a fine particle (<0.1 cm) took maximum days for decomposition.

4.4.7.4 Soil Properties

Decomposition of plant parts is generally faster in soil with lower clay content as clay sheltered SOM. Soil texture also affects soil physical environment, which further influences microbial activities. Soil pH affects both the nature and size of the microbial population, which eventually determine the rate of CR decomposition. In general, decomposition of CRs proceeds faster in neutral soil over acidic soil. As a result, applications of lime in acid soil improve the decomposition of CRs (Jenkinson (1971).

4.4.8 In Situ Mulching of Crop Residue

4.4.8.1 Rice-Wheat-Based System

Emerging CRM practices for IGPs to avoid residue burning include mulching of rice residue with NT in wheat. A huge quantity of paddy residue production in combined harvesting hampers NT planting for succeeding wheat owing to residue accumulation in seed-drill furrow opener and reduced traction of seed metering devices because of the presence of CRs. As availability of suitable types of machinery was a key problem to direct-drill in heavy paddy stubbles, planning of utilization of new generation machine for planting in CRs done by Happy Seeders.

4.4.8.2 Non-rice-Wheat-Based System

Resource conservation is the most important for sustainable crop production in semi-arid regions because of the high rate of evapotranspiration (ET). Apart from the adjustment of a growing period of paddy in Punjab, mulches are the only practice that reduces ET through reducing evaporation (Prihar et al. 2010). Several researchers had reported a significant increase in yield, reduction in irrigation, and increase in water productivity and nutrient use efficiency (NUE) by changing the hydrothermal regime of soil (Jalota et al. 2007; Dhakal et al. 2016). The quantity of yield increased in many crops ranging from 4 to 29% (Jalota et al. 2007). The advantage of mulching depends on temperature, rainfall, irrigation regime, soil texture, and type of mulching material being used. The response is better at high temperature, lesser rainfall, and in coarse-textured soil. Higher moisture in the soil profile in root zone under mulch plot improved crop establishment and seeding vigors. Arora et al. (2010) reported a 19% increased yield of soybean due to wheat straw mulch compared to un-mulch. Higher yield and water productivity were attained in deeper and denser rooting due to NT/RT which encouraged a decrease in soil mechanical resistance along with regulated soil temperature and moisture conservation by tillage and straw mulches (Singh et al. 2017a, b, c).

4.5 Conservation Agriculture and Crop Residue Management on Surface

Conservation agriculture is known as "agriculture of the future, the future of agriculture." The CA crop management practices, viz., NT with retention of CRs on the surface and proper rotation of crop, are seeking much attention because of deterioration of natural resources (soil and water). The potential benefit of NT can be realized only when it is practiced continuously and soil surface remained covered with CRs at least 30% (Arora et al. 2010). Agronomic productivity and profitability are higher with using CRs along with NT under CA (Jat et al. 2014a, b; Meena et al. 2015a). After conducting many trials at PAU, Ludhiana, on sandy loam soil, it was found that there was ~43% increase in wheat yield with using straw mulch compared with no-mulch in double ZT. At the same time, there is not much dramatic difference in wheat yield (2.4–5.4%) as compared with the use of rice straw mulch in CT-puddled transplanted rice + no-mulch. Managing wheat straw in DSR and rice straw in wheat increased the productivity of system and WUE in RWCS under permanent NT system. Assurance of good seed germination and crop establishment are the prime challenges faced by CA. Three machines, i.e., double disc opener drill, turbo happy seeder, and rotary powered disc drill, which are capable of seeding even into fully surface-retained rice residues are now accessible. Double disc opener drill works well up to residues load of 4.0 t ha^{-1}. These drills may have greater application when the crop is raised on a permanent raised bed in the rice-maize system. Rotary powered disc drill is a modification of rotavator, in which rotary tiller blades are replaced with plain disc colters. In rice field, powered colter gets blunt after every 25 ha of its operation due to high Si in rice residue.

Nine-rowed turbo happy seeder is energy efficient and performs seeding under NT wheat under heavy load of rice residue (9 t ha^{-1}).

4.5.1 Effect of Surface Residue Retention on Crop and Soil

4.5.1.1 Effect of Surface Residues on Crop Yield and Water Productivity

Organic nutrient sources and CRs are the primary sources of C input, and its management practices have a significant effect on the physical, chemical, and biological properties of the soil (Kumar and Goh 2000). Incorporation of CRs alters the physicochemical environment of the soil which in turn influences the microbial population in soil and subsequent nutrient transformation. In general, soil enzymes are good markers of soil fertility since they are involved in the cycling of the most important nutrient making them in plant available form which affects the plant growth and yield parameters. Findings from different location of an on-farm trial conducted during 2007–2010 in Punjab reported that happy seeder planted wheat produced significantly higher yield (3.24%) than CT (Sidhu et al. 2011). In another study, Chakraborty et al. (2010) concluded that rice straw mulching significantly enhanced grain yield of wheat by 17.1%, reduced water requirement by 3–5%, and improved water productivity by 38.3% in comparison to no-mulch. Planting of wheat on residual soil moisture without pre-sowing irrigation saved 20% irrigation water, which helps to save 80 kWh of electric and cut down the emission of 160 kg of CO2 (Bohra and Kumar 2015; Verma et al. 2015c).

4.5.1.2 Soil Erosion, Moisture, and Temperature

Residue used as mulch under NT system supplies multiple benefits, i.e., soil moisture conservation, enhancing soil quality, and a decrease in GHG emission. Retension of crop residues on the soil surface moderates the soil temperature which reduces by 10°C at 5.0 cm soil depth during summer. Furthermore, straw mulch lowers canopy temperature by 2.9°C at grain filling stage and helps to mitigate terminal heat stress in wheat (Jat et al. 2009; Dadhich et al. 2015). Economic outcome of CRs as mulch on soil moisture and temperature change can affect germination, seedling growth, N fixation, and root growth, which ultimately determine the crop yield. Singh et al. (2011a) reported that the use of rice straw as mulch in wheat in IGPs of India reduced evaporation by 42–48 mm during the growing period. CRs left on soil surface increased fallow efficiencies and rain proportion that are reserved up to 75% compared to no-mulch and minimized the physical force of raindrop on soil, increased the rate of infiltration, and reduced runoff resulting in an increase of stored soil water under the rainfed agro-ecosystem.

4.5.1.3 Effect of Surface Crop Residues on Nutrient Management

CRs may supply 35–50 kg N ha^{-1}, which is foremost to consider in the optimization of N under CA. Singh et al. (2005) standardized the use of 20–40 kg ha^{-1} extra N during first few years after residue incorporation due to volatilization loss of N. Afterward, recommended fertilizer application could be used to attain higher productivity of yield of RWCS. NT practice with surface CRR often shows repressed yield associated with poor N availability due to the slow rate of N mineralization, a higher rate of N immobilization, denitrification, and NH3 volatilization, particularly during early growing season compared with CT. The minimum contact of N fertilizer with a straw through drilling fertilizers below the soil surface to reduce the immobilization and volatilization. Wheat sown into rice residue generally responds to application of N up to 120 kg ha^{-1} similar to CT (Singh et al. 2010b, Meena et al. 2011a, b, c, d). The buildup of SOM and improvement of readily mineralized N with residue recycling indicate the potential for reducing fertilizer N for optimal yield of the following crop after several years of residue incorporation (Mishra et al. 2017). Therefore, adjustment in timing and rate of N fertilizer are necessary to optimize the N supply to crop receiving CRs (Neupane et al. 2011a, b, c; Paswan et al. 2017a, b). Nitrogenous fertilizer is necessary for paddy to obtain targeted agronomic efficiency of N noted. In CA, broadcasting of N fertilizers on the residue-covered soil surface is a non-efficient means due to higher immobilization potential of surface residue and volatilization loss of N (Saurabh et al. 2015, 2018a). The probable remedy for volatilization and N immobilization could be to put fertilizer in the band below C-enriched surface soil, which is the result of the surface placement of CRs. For seed row placement, applying di-ammonium phosphates (DAP) at 130 kg ha^{-1} along with 56 kg urea ha^{-1} exhibits no impact on wheat yield. Further, the increase in doses of urea along with DAP would show an adverse effect on the germination and wheat yield. Thus, drilling of 80% recommended dose of N (120 kg N ha^{-1}) along with P and K at seeding in middle of two adjacent wheat row with significant increment in grain yield over broadcasting in two equal split (Singh et al. 2015; Ray et al. 2016a, b; Meena et al. 2015c).

4.5.2 Crop Residues as Biochar

Because of relative stability in the biological condition of biochar, its soil-applied product has been introduced as a path to divert waste carbon biomass from a rapid to a slow carbon cycling pool. During the last few years, concern for quality production of food and environment safety along with maintaining soil health acquired attention to improving SOM by suitable soil management practices. Haefele et al. (2011) concluded from their study that biochar made from rice residues may be useful in rice-based systems but real influence on soil fertility, yields, and SOC will depend on site-specific management. As it is ready to react surface and recalcitrant aromatic structure; soil biochar could affect many biogeochemical processes and works as a sink for atmospheric CO2. Upon pyrolysis of waste biomass, ~50% of C in biomass is instantly released which may be useful in energy production to offset fossil fuel, lifting a biochemically recalcitrant biochar residue (Lehmann et al. 2006; Datta et al. 2017b), whereas 80–90% of biomass C in original form is produced as CO2 within 1–10 years, depending on soil and climatic circumstance. Biochar offers the significant prospect for sequestering 40–50% of C biomass in the soil in a chemically changed form that is biologically stable and could last in the soil for centuries but remains active in physical and chemical form. Intractable nature of biochar makes it suitable as an organic amendment with potential for GHG mitigation, but little investigations have been undertaken to document such benefit. Due to its more stability against microbial decomposition and its superior capacity to hold nutrients in comparison to another form of SOM. Applying biochar offers significant potential in reducing the effect of climate change. Biochar can stimulate native soil microbes and their activities and provide congenial habitation for microbe and encouraged VAM fungal colonization for enhancing the moisture and nutrition supply besides promoting rhizobacteria for N fixation in the leguminous plant. Currently, few findings were reported by various researchers on a different aspect of biochar use in the different cropping system. Long-term findings on biochar seem necessary to understand the effect of biochar and its behavior in different soils of IGPs of South Asia.

4.5.3 Use of Crop Residue for Composting

Composting from cattle manure with rice straw is an important option that could offer many environmental and economic benefits in IGPs, where manures and straw are easily available. This composting helps in improving the soil moisture and nutrient balance to the microorganism. Composting process is affected by a number of factors, and the most important factors are moisture content, temperature, aeration, pH, C:N ratio, and physical composition of the raw product. In IARI, the rate of decomposition, which is hastened by a consortium of microorganisms almost, takes ~75–90 days. PAU technology for preparing high-value rice straw compost includes the use of indigenous low-grading rock phosphate to make it value-added compost with 1.5% N, 2.3% P2O5, and 2.5% K2O. Residues of paddy from 1 ha, on composting, give ~ 3-ton manure, which is rich in nutrients in comparison to farmyard manure (FYM). At Modipuram, CR decomposition was increased by using cellulolytic fungi (Jat et al. 2004) and mineral salt (Pal and Jat 2004). By using compost, made from straw of CRs, there was decreased requirement of 50% of N and P under RWCS. In animal shed, each kg of straw can absorb 2–3 kg animal urine which has a high content of N. Long-term sustainability of any cropping system mainly depends on carbon input, output, and carbon use efficiency. Long-term straw application will build SOM and N reserve, increase the availability of macro- and micronutrients, and affect soil microbes and their activities and subsequent nutrient transformations (Singh et al. 2005; Ram and Meena 2014). Cereal residue retained at surface checks soil erosion by buffering action of the raindrop and lowering the wind speed. Residues increase the water availability in the soil for the plant which improves water infiltration and checks evaporation losses from the soil surface. CRR either on soil surface or their incorporation into the soil over long term enhances OM content, decreases losses of plant nutrients, and increases nutrient holding capacity and microbial activities in the soil system. Removal of plant nutrients from CRs depends on residue type, the quantity of residue removed, climate, tillage, SOM, decomposition rate, and other practices. Long-term effects of removal of high levels of CRs lead to a net amount of losses of plant nutrients under fertilization practices. Retention of CRs helps for enhancing physicochemical properties of soil, i.e., infiltration rate, available water, soil structure, nutrient cycling, cation exchange capacity (CEC), soil reaction, and biological properties, viz., microbial biomass, SOC sequestration, activity, and species diversity of soil flora (Singh et al. 2008; Meena et al. 2017a). Infiltration rate and hydraulic conductivity are highest in soil under residue retention in comparison to CT. It might be due to larger macropore conductivity resulting in an increased number of bio-pores that is commonly observed. Rice residue in wheat can help in reducing the negative impact on hardpan in RWCS and is advantageous to wheat. Crop residues are known to enhance BNF in soil by symbiotic bacteria. Mulches provide a better environment for microorganism, which helps for improving BNF owing to increase in nodulation in pulses crop. CRR increases aerobic bacteria by 5–10 times and fungi by 1.5–11 times as compared with removal or burning residues (Beri et al. 1995). Different enzymatic activities, i.e., dehydrogenase and phosphatase, are increased over residue removal. Soil has higher carbon sinking power, though the sinking ability or sequestration rate cannot be continued for an indefinite period. On the basis of changes in SOC and quantity of carbon used, 12–25% of applied paddy residues-carbon was impounded by loamy sand soil after 3–7 years (Singh and Sidhu 2014; Verma et al. 2015b). Carbon sequestration rate is mainly affected by soil type and climatic condition. The optimum level of carbon input necessary to maintain SOC at precursor level is ~2.47 t ha^{-1} $year^{-1}$ in RWCS (Srinivasarao et al. 2013). Sequestration of SOC would assist to lower the GHG emission, increase productivity, and reduce ecological damage due to the burning of CRs and exhaustive tillage. Carbon trading will provide a monetary opening for farmers toward adopting this cost-effective approach.

4.5.4 Crop Residue and Bio-energy Options

Surplus CRs might be used for bio-energy generation. Bio-energy potential from total excess residues in India would be ~4.15 EJ $year^{-1}$ (Hiloidhari et al. 2014). This is 17% of the prime source of energy consumption (24.91 EJ) in India, and cereal contributes the highest (1.49 EJ). There are different ways in which CRs are used as biofuel or source of bio-power. Major biofuel option for CRs is cellulose-ethanol production that engaged in enzymatic breakdown of cellulose of residue into sugar, which can ferment into ethanol. One of the bio-power options is burning residue alone or in combination with coal to produce steam to force a turbine that turns an electric generator. Another bio-power alternative is gasification in which residue is burned in presence of partial O2 to form a gas mixture of N2, H2, CO, and CO2 recognized as producers/synthesis gas and pyrolysis under which residues are burned in presence of O2 to form a high-energy liquid. Anaerobic digestion of residue produces biogas, where CRs are blended with other wastes, i.e., manures, permitted toward decomposing anaerobic and burned to create electricity. The bulk of residue, mainly paddy straw per se, is an ineffective fuel basis. Calorific values of rice residue are very less (14–16 MJ kg^{-1}) than steam coal (Singh et al. 2008; Meena et al. 2017b). Presently, the entire potential for rice residue use for bio-energy possibly will not be ≥10% of overall crop residue in Punjab. It would be healthier for sustainable production if residue is retained before aloof for bio-energy.

4.5.5 Crop Residue Management and Disease-Pest Dynamics

CRs used as mulch had great potential to manage weeds, thereby suppressing the negative effect of weeding force in minimum/NT. Straw mulching effectively controls weed expansion through smothering or allelopathic effect (Singh and Sidhu 2014), and it reduces herbicidal requirement and weed competition for nutrient and moisture. Retention of CRs on soil surface is often linked to better occurrence of diseases in the crop. In NT, it can intensify soil-borne disease owing to less disturbance and retaining of CRs on the surface. However, intermittent residue incorporated under NT can inhibit pathogen expansion by forcing it into a place of inadequate air and lighting. Mulching favors survival of soil-borne pathogen as this saved microbial degradation via residing within crop debris (Singh et al. 2008). Mulching might curb soil-borne pathogen, as it increases the population of soil micro- and mesofauna, which offers a potential for biological disease control as a lot of these species nourish on fungi. In a few studies of residue effect on disease in RWCS, wheat sown with NT along with paddy straw had a minimum occurrence of *Tilletia* (Sharma et al. 2007). If a disease/insect can be sufficiently managed through crop rotation and cost-effective application of pesticide, mulches would turn into a smart CRM practice for mitigating of insect pests in wheat under RWCS.

4.6 Climate Regulation: Emissions of Greenhouse Gases (GHGs)

This deal with the net emission of GHG, i.e., N_2O and CH_4 from the soil as a result of CA. It is crucial to note that there is a significant impact of CA as compared to conventional agriculture in terms of changing in the intensity of mechanical tillage and lower irrigation, and perhaps minimum use of N fertilizers abridged employing of fossils fuel through CA (Pathak 2009).

4.6.1 Crop Residue Management and GHGs

The immediate effect of cereal residue (wheat) incorporation into rice field comprises stimulation of CH_4 gas emission, immobilization of available N, reducing the growth of paddy, and accumulation of phytotoxic material (Singh et al. 2008; Meena et al. 2018a). Incorporation of residue in a rice field at an optimal timing in advance of paddy planting helped to minimize the negative effect on paddy and CH_4 emission. Incorporation of wheat residue prior to planting of paddy may reduce N_2O emission because of immobilization of mineral N through high C:N ratio of residue. However, the increase in N_2O emission from the field with mulches in contrast to those with integrated residue was noticed in RWCS. Manipulating in the timing of CRs in such a way so that N becomes accessible while required by upland crops must minimize N_2O emission in relation to residue return at the beginning of pre-season fallow. CRs are unlikely to have a considerable effect on CH_4 release in upland crops. For CH_4, there must be anaerobic micro-sites of methanogenic bacteria. Any action that causes residue to decompose prior to fit anaerobic will reduce risks of CH_4 emission.

4.6.1.1 Nitrous Oxide (N_2O)

N_2O is the powerful and long-lasting GHG having global warming potential (GWP) of 298 times than CO2, and it remains in the atmosphere up to 114 years. N_2O is produced by microbial transformations, i.e., nitrification and denitrification in soil. Nitrification-oxidation of NH4 to NO3- occurs under aerobic situations, whereas denitrification-reduction of nitrate (NO3-) to N_2O and N2- takes place in anaerobic condition. Frequency and quantity of N_2O emission are linked with soil structure that has a role in bulk density, soil carbon, and aggregation. Nitrification is a key source of N_2O at lower soil moisture content (water-filled pore space <40%) (Werner et al. 2006), whereas contribution from denitrification increased at water-filled pore space above 65–75%. N2/N_2O ratio increases with the formation of N_2O at water-filled pore space >80–90% (Dalal et al. 2003). The bulk density of soil is generally higher in NT than in CT; so, water-filled pore space will be more due to the anaerobic situation; denitrification is greatly tempted earlier at equal water content in NT. Managing of CRs and crop rotation could affect N_2O emission by altering the accessibility of NO3- in soil and decomposable carbon substrates (Firestone and Davidson 1989). Retaining CRs and subsequent addition of SOC under CA play an important role in these processes. Emission of N_2O increased with application of N fertilizers by rising N accessibility in soil (Davidson 2009). Legume residue resulted in more N_2O-N loss (Millar et al. 2004) than non-leguminous crops (Yao et al. 2009; Meena et al. 2017c). The lower-quality residue of cereal (C:N ratio >25) along with surface applied residue in CA resulted in N immobilization and reduced N_2O release than CT. The amount of leguminous residue back to the soil is considerably lowered (Peoples et al. 2009). Lower soil temperature and improved soil structure in NT can reduce the occurrence of soil saturation and emission of N_2O. The finding from different field shows that wet soil along with higher availability of C in NT increased emission of N_2O (Yao et al. 2009). Pandey et al. (2012) also reported the lowest N_2O emission in NT/RT.

4.6.1.2 Methane (CH_4)

CH_4 had 12 years life and GWP of 25 times higher than CO2 over 100 years' time horizon. Agriculture land contributes to CH_4 emission through methanogenesis under saturated situation linked with paddy cultivation. Lowland paddy production system contributes ~15% of the total world's CH_4 emission (IPCC 2001). Organic fertilizer has a great potential toward increasing emission in excess of 50% relative to non-organic fertilizers (Yao et al. 2009). On contrary to N_2O (Chapuis-Lardy et al. 2007), CH_4 may be utilized by soil microorganisms, consequently in a CH_4 sink, which is sensitive to both temperature and water content (Dalal et al. 2008). Agricultural lands, particularly those that are fertile, had notably the lowest CH_4 oxidation rate than uncultivated lands (Jacinthe and Lal 2005) and highest with temperate lands. Retention of CRs is an easily accessible source of C that increases CH_4 emission from a paddy field in anaerobic condition (Zou et al. 2005).

4.7 Soil Carbon Sequestration and Findings of Conservation Agriculture

It refer to increase C stored in soils by arresting atmospheric CO2 as a result of change in land use pattern (Powlson et al. 2011). Whereas, CA was not firstly envisaged as a way to sequester C, it is currently considered as a probable technique to mitigate GHG emission (Corsi et al. 2012). Soil carbon sequestration as that C which is supposed in further recalcitrant form and less vulnerable to loss from decay (West and Marland 2002).

4.7.1 Tillage

NT, a major component of CA, increases SOC content in comparison to CT; however, this increase is mostly limited to close surface layer (<10 cm). On deeper depth, C under CA can be equally or even lower than CA. It mainly depends on precursor soil C content, management period, cropping system, soil texture, slope, and climate (Luo et al. 2010).

4.7.2 Crop Rotations

Crop rotation has a lesser effect on soil carbon compared to tillage practices. It affects soil carbon by increasing production of biomass and carbon inputs from various crops under cropping system, diversified root pattern and root depth (Corsi et al. 2012). More residues generating crop might sequester extra C as compared to lower residue producing input. Intensive cropping system means an increasing crop every year, second cropping, and inclusion of smother crop causes improved soil C storage under NT (Luo et al. 2010). Managing the frequency and type of tillage can stop soil degradation and improve soil quality. Tillage disrupts soil aggregates exposing organic matter to microbial degradation. These changes in

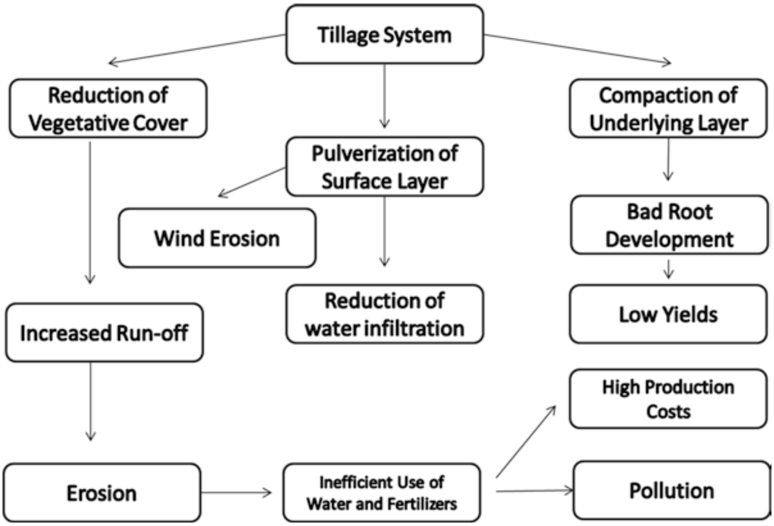

Fig. 4.7 Effect of tillage on plant yield and environment

structure can affect soil water, temperature, aeration, and equilibrium of reactions and increase soil erosion (Fig. 4.7).

4.7.3 Residue Maintenance

Retention of CRs is an important component of CA for improving C pool in the soil. Causes that increased crop harvest will increase the amount of CR availability and thus potentially of soil C pool. Nutrient management is the most vital factor to increase residue production and finally soil C sink, whether the system is NT/CT included in crop rotation (Giller et al. 2009). These are the main reason for rising C input and soil carbon in lower inputs and lower productivity as found in some parts of South Asia (Paul et al. 2013). Similarly, lacking response to 4 Mg ha^{-1} of CRs followed for 4 years of incorporation was noted in a subtropical region of Nepal (Ghimire et al. 2012). Different effect of CA practices along with their conjunction on soil processes, ecosystem, and how these changed by environment and soil type is essential toward creating analytical thought that may be used for better and location-precise CA planning.

4.8 Biological Properties

Microflora (bacteria, fungi), microfauna (nematode, protozoa), mesofauna (acarid, enchytraea), and macro-fauna (termites, earthworm, arthropod) are together called soil biodiversity. Type of cultivation practices and cropping system being adopted affect land/soil diversity in various ways positively or negatively. Addition of fertilizer and manure which alter C:N ratio and tillage practices play a great role in the maintenance of agro-ecosystem.

4.8.1 Microbial Activities

Important characteristics of the soil, viz., soil moisture, soil structure, and nutrient availability in agro-ecosystem, are controlled by decomposition of SOM carried out by a diverse group of soil microorganisms. Biomass of soil microbes (SMB) defies as live part of SOM. It has been projected as another important sign of soil quality, as it is the basis as well as a pool of organically available nutrients and promotes the formation of soil structure and aggregation. Availability of soil microbes is possibly influenced by temperature, moisture, and management practices (Govaerts et al. 2007; Meena et al. 2015b). CRs of rice have a significant effect on stimulating SMB and microbial activities in the soil. Lou et al. (2011) compared treatment with or without the inclusion of CRR and noted markedly higher SMBC level that was recorded. Residues retention in the field, enhanced C and N content, improved soil porosity, and decreased soil temperature were observed. Integration of residue accelerates aeration, moderates the soil temperature, and creates favorable conditions for soil microorganism and better contact with CRs, which results in higher rate of decomposition and overall losses of SOC (Fontaine et al. 2007). Under tropical and subtropical regions, where temperature and precipitation are high, CRRs of rice along with NT had increased SOC on topsoil compared to soil incorporation (Bayer et al. 2000). It is mainly owing to the hindrance of contact between CRs and microbes in NT soil; thus, decomposition rates are low. Arbuscular mycorrhizal fungi (AMF) help in recovering nutritional accessibility to plant. AMF is an example of symbiotic relationships among plant root and fungi, where plant exudates provide glucose to fungi and from fungal hyphae phosphate is delivered to plant roots. In addition to AMF hyphae and secretion of glycoprotein, glomalin helps in soil particle binding, which improves the stability of aggregate of the soil. SOM inputs had an encouraging effect on AMF development and spores (Emmanuel et al. 2010), whereas unrest soil by tillage is recognized as harmful to AMF hyphae (Usuki et al. 2007). Samal et al. (2017) deliberated alteration in microbial properties under a long-term scenario in RWCS and observed that highest SMBC was recorded in 0–10 cm soil depth under the following of conservation agricultural practices (89.32 ± 3.46 μg C g^{-1} soils). Microbial attributes (MBC, FDA) were therefore enhanced with an increase in residue-C addition and build SOC stock.

4.8.2 Earthworms

As larger soil fauna or soil macro-fauna, earthworms play a key role in the soil environment. Earthworms improve water movement, soil structure, nutrient recycling, and plant health. These are not the only indicators of healthy soil, but also their existence is a pointer of a healthy cropping system. They in straight line affect C and N cycles by overriding, collection, and recycling of plant nutrients by their biomass, releasing the significant amount of N through discharge (Whalen et al. 2000). They improve SOM in course of their guts and structure like cast, burrow, and midden, which ultimately influence soil aggregate stability and ultimately effect on C and N cycle. Earthworm responds positively to CRs and NT because it improved the physicochemical properties of the soil (Errouissi et al. 2011). Low soil temperature helps in prolonged CRR on the soil surface, which acts as food reservoir to the worms leading in their increased number and biomass (Kumawat et al. 2009a, b, c, 2013a, b). Thus, CRRs had a varying consequence on earthworm population; however, it depends on their ecological niche (Wuest et al. 2005; Metzke et al. 2007). Consequence of CRs on soil fauna including earthworm depends on types of tillage, tillage rate, plowing depth along with application method, type, amount, and quality of CRs (Mandal et al. 2011a, b; Kumar et al. 2015b, c, d), Kumar 2017, Kumawat et al. 2017a, b, c). Soil microbes cooperate significant function in mediating alteration in TOC through mineralization-immobilization of SOM (Breulmann et al. 2014). The procedure of straw decomposition is interceded by soil microbes and is exaggerated by soil texture, straw quality, and climatic condition (Chen et al. 2014, Kumawat et al. 2016a, b; Kumar et al. 2017a, b, 2018a, b). Soil microbial population responds in a different way to straw decomposition (Marschner et al. 2011). During 1st stages, bacteria dominated in microbial communities; fungus dictated later stages (Zhao et al. 2016).

4.9 Summary and Conclusion

The decline in resources like water scarcity and crop factor productivity and natural resources are alarming to agriculture sustainability in South Asia. Diversification of traditional RWCS through CA-based intensification may be a better alternative of aiming the twin goal of improving farm productivity while talking about the issues of lower water productivity. A key role is played by CRs in the recycling of plant nutrient despite the dominant role of synthetic fertilizer in crop production. CRM can control the efficiency of fertilizer, water, and other critical NRM. Due to intensive RWCS that prevailed in SA, it is required to manage a huge quantity of residues, which are a good source of C, N, and K. Thus, we should incorporate that practice which improves SOM and crop productivity and replace chemical plant nutrient with CRs. After harvesting of rice/wheat, there is sufficient time to sow the green manure crop, which has a big substitute of 50% of N needs to rice. Thus, residue quality must be taken into account in soil management. Another important practice is the placement of these residues in the field when CRs are retained on soil surface. This not only minimizes soil loss by erosion but also increases soil physical health and improves SOM specifically in the upper layer. Besides, proliferation of soil microbes' population and their activities after CR addition can increase the nutrient supplying ability of soil and reduces nutrient losses. Addition of CRs by tillage may decrease SOC storage via an elevation in the decomposition process in comparison to CT practice. Acidic soil can be ameliorated by incorporation of CRs. Burning of CRs is useful in the short term because burnt CRs can directly add ash alkalinity to soil from oxidations of organic anion in CRs. On the contrary, the effect of long-term residue burning can hasten soil erosion, badly affects soil physical condition, and increases the loss of SOM and related nutrient. CRM options, quality, and quantity of residues return back to the soil and affect soil fertility in course sequence of physicochemical as well as biological alteration in the soil. A consistent indicator of soil property change that shows a relationship by means of a vital aspect of soil physicochemical and biological properties possibly will offer a base for sustainable CRM strategies. Change in unstable SOM fractions, soil microbial population, and their functions are a reliable indicator of alteration in soil properties due to variation in CRM.

4.10 Research to Be Needed

This book chapter mainly emphasized on needs of long-term experiments to perceive the influence of CRM practices in South Asia. In addition, it highlights practices that involve a combination of intervention at the farm level to design system that preserved soil health for maximum crop production. To distinguish the nutrient providing capacity through CRs under RWCS in IGPs, there is a requirement of analysis of yield of both above- and below-ground crop residues. More literature is required to be compiled on the effect of management including soil tillage, residue placement, residue quality, residue quantity, soil type, soil moisture, temperature, cropping system on decomposition, and nutrient release rates. Development of techniques for fast in situ decomposition of CRs by irrigation, fertilization, tillage, and use of decomposing microbial consortia for RWCS is required. Long-term experiment regarding soil property changes and nutrient cycling is needed to be performed as many soil qualities may be clearly visible after 10 or more years of CRM. Thus, there is a necessity to start long-term field's experiment at different site judiciously selected for deviations in temperature, moistures, soil mineralogy, and agricultural management system covering RWCS in IGPs of South Asia.

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Improved Soil Environment Under Conservation Agriculture

5

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Contents

Abstract

The natural resources are continuously depleting because of the intensive agricultural operation, the insufficient return of organic matter (OM) to the soil, and continuous monocropping system. Along with OM depletion, erosion and soil salinization are aggravating the problems of resource depletion several times. For achieving food security and alleviation of hunger and poverty, there is a need of a sustainable agricultural production technology, which will be able to conserve the natural resources and will be capable of reducing the harmful effect on the environment. Under these circumstances, conservation agriculture (CA) has come to be a promising production technology which consists of minimum soil disturbance, permanent soil cover maintenance by means of cover crops and/or crop residues, and crop diversification for attaining higher crop productivity and

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subsequently decreasing the adverse environmental effects. It is also referred to as resource efficient or resource effective agriculture. The ultimate aim of CA is to achieve satisfactory returns and greater plus persistent crop production and, at the same time, to conserve the environment. The prime goal of CA is to reduce the adverse impact of traditional agriculture and burning or removal of crop residue. Right now, CA is followed on approximately 157 million ha arable land worldwide. CA can effectively conserve and use the natural resources as it involves integrated management of soil, available water, and biological resources along with the judicial use of external inputs. In CA, good agronomic practices like timely farm operations, quality seeds use, and integrated weed, nutrient, pest, as well as water management are followed. The yield under CA system is at par with the conventional system. Residue retained on the surface of soil helps in improving soil quality, plant health, and overall resource use efficiencies. CA practices can improve the water and nutrient use efficiencies by enhancing nutrient balances and availability, infiltration, and water retention in soils; by reducing evaporation losses; and by enhancing the surface and subsurface water quality and availability. As the pragmatism of CA in various parts of the globe is governed by the biophysical and socioeconomic challenges, an adaptation of CA should be as per the site and farmer's condition. As CA requires better understanding and knowledge, convincing the farmers through proof is the most important task in motivating the farmers for adopting CA. In this chapter, an attempt has been made to describe how CA can modify and improve the soil physical environment.

Keywords

Conservation agriculture · Intensive agriculture · Soil health · Soil organic carbon · Soil temperature · Zero tillage

Abbreviations

BD	Bulk density
CA	Conservation agriculture
CT	Conventional tillage
CTF	Controlled traffic farming
DSR	Direct-seeded rice
FAO	Food and Agriculture Organization
GAP	Good agronomic practices
GHGs	Greenhouse gases
GPS	Global positioning systems
HYVs	High-yielding varieties
IGP	Indo-Gangetic Plain
IPM	Integrated pest management
MWD	Mean weight diameter

NT	No-tillage
OM	Organic matter
RT	Reduced tillage
SOC	Soil organic carbon
WUE	Water-use efficiency

5.1 Introduction

In intensive agricultural practices with less return of organic matter (OM) to the soil and continuous monocropping system, the result is that the natural resources are incessantly exhausting. Besides OM depletion, erosion and soil salinization are aggravating the problems manifold. Along with this, the adverse impact of climate change, rising inputs cost, and volatile market prices of food commodities are escalating the problems. For achieving the food security and alleviation of hunger and poverty, there is a need of sustainable agricultural production technology, which will be able to conserve the natural resources and will be capable of reducing the harmful effect on the environment. Intensive tillage and prevailing traditional agricultural practices led to the declined OM due to rapid and higher oxidation with time, causing loss of soil biological activity and fertility, soil degradation, and reduced resilience of soil (Lal 1992; Meena et al. 2018a). Conservation agriculture (CA) has to turn out to be a promising technology which involves minimum disturbance of soil, keeping a soil covered permanently by means of crop residues/cover crops and crop diversification for attaining greater crop productivity and at the same time reducing the negative environmental effects (Hobbs 2007; FAO 2011a, b, c; Meena et al. 2015c). In the recent FAO (2012) report, the area under CA has sharply increased worldwide which covers about ~8% of the total world arable land (124.8 M ha). Hence, CA is an approach of cultivating annual and perennial crops. Zero tillage (ZT) and reduced tillage along with crop residue retention and cover crops are appropriate for maintaining permanent soil cover and increasing OM content in soil naturally (Bhan and Behera 2014; Yadav et al. 2017a). CA-based technologies are ZT with residue retention, laser land leveling, direct-seeded rice (DSR), brown manuring, and crop diversification (Chakrabarti et al. 2014; Meena and Meena 2017). As seedbed preparation time is very short, ZT helps in timely crop establishment along with comparable yields and reduced input costs (Das et al. 2013; Sofi et al. 2018). Besides, crop residue retention on soil surface helps to improve soil and crop health, protects soil from the destructive raindrops action, enhances canopy transpiration, and reduces evaporation loss (Aggarwal et al. 2017; Kakraliya et al. 2018). In CA, there are savings of labor, water, and energy and reduction in greenhouse gas (GHG) emission along with improved nutrient and water-use efficiency (WUE). Crops grown under CA become more heat and water stress tolerant. Thus, CA helps in improving water use, nutrient uptake, and soil organic carbon (SOC) pool (Dahiya et al. 2007; Verhulst et al. 2011; Bhattacharyya et al. 2013; Yadav et al. 2018a), moderates the soil hydrothermal regimes (Aggarwal et al. 2009a, b; Pramanik et al. 2015; Meena et al. 2016), and improved root water uptake (Aggarwal et al. 2017; Mitran et al. 2018) and soil physical health (Rai et al. 2018; Kumar et al. 2018) and ecosystem services (Pathak et al. 2017). In the subsequent sections, we will discuss in details how CA improves the soil environment.

5.1.1 Intensive Agriculture and Soil

Intensive agriculture is associated with high doses of input use and more expected output per unit of agricultural land. Typical characteristics of intensive agriculture are high cropping intensity; low fallow period; higher use of fertilizer, irrigation, and labor; and greater crop yields per unit land area. With the rapid increase in population and subsequent high food demand, the subsistence farming system becomes under pressure because of limited area available for agriculture (Ram and Meena 2014). This led to the agricultural intensification which involves the use of high-yielding varieties (HYVs), synthetic fertilizers, irrigation water, and improved agronomic practices (Marks and Britton 1989) causing a manifold increase in crop productivity. In intensive farming, crop productivity is high which can meet the rising food market demand. Furthermore, in intensive farming, land requirement is also less. Slowly over the years, intensive agriculture has succeeded and become more efficient. Recently, the adverse impacts of intensive agriculture on the environment and society have become more prominent. Improved agricultural technologies and prevailing practices, like monocropping, synthetic fertilization, indiscriminate use of pesticides, intensive tillage, and farm operations through heavy machinery, improved soil, and irrigation management, considerably disturbed soil quality by changing physical, chemical, and biological properties of soil (Fauci and Dick 1994; Meena et al. 2014). Soil erosion, SOC depletion, loss of biodiversity, contamination, surface sealing, subsurface compaction, salinization, and landslides have become main threats (Andrews and Carroll 2001). Use of heavy machinery during farm operations like terracing, land leveling, and deep plowing causes major landscape modifications and land degradation (Borselli et al. 2006). Also the heavy machinery use during farm operations alters the soil surface characteristics, which leads to the changes in hydraulic properties like soil infiltration (Léonard and Andrieux 1998; Meena et al. 2015b), geomorphologic processes like erosion of soil (Lundekvam et al. 2003), and also mass movements (at the time of heavy rainfall). Studies reported that farm operations with heavy machinery create spatial variability in soil properties which causes heterogeneous infiltration and runoff in sloppy areas (Meena et al. 2015a). Wrong agricultural practices have deteriorated soil quality, SOC losses and structural degradation, disturbed water, air, and nutrient movement, and subsequently plant growth (Golchin et al. 1995). Excessive application of irrigation water may cause surface soil crusting, higher runoff, surface and groundwater contamination, and more greenhouse gases (GHGs) like carbon dioxide (CO2) and methane (CH4) emission. When excessive untreated wastewater is used for irrigation, then it may cause soil structure degradation, soil aggregate stability and hydraulic conductivity deterioration, surface sealing and runoff, soil erosion and compaction, and a decline in aeration status of soil (Meena and Lal 2018). Intensive agricultural practices might be responsible for the degradation of macrostructure resulting in (< 2 mm diameter size smaller) aggregates (Aina 1979). Studies reported a considerable decrease in the stability of soil aggregate in intensive agriculture. Heavy machinery traffic modified the aggregate size which led to the small to large pore ratio (Silva and Mielniczuk 1998).

Indiscriminate and untimely applications (Dungait et al. 2012; Meena et al. 2017a) of synthetic fertilizer during the crop growth period caused huge loss of nutrients (Nitrogen, Phosphorus, etc.) to the water bodies through percolation, leaching, and runoff leading to the increased emission of GHGs like ammonia, methane, nitrous oxide, and other volatile compounds. Soil pollution is associated with the indiscriminate use of fertilizers. Nitrogen in nitrate (NO3-N) form is highly soluble and is leached to groundwater. Punjab and Haryana are categorized into the high-risk zone of nitrate pollution due to higher use of nitrogenous fertilizer. Phosphatic fertilizers contain trace elements like cadmium, chromium, mercury, nickel, arsenic, and lead (Pathak et al. 2013). These possibly damaging elements may gather in soil and may affect crop yields and quality on long term. Through food and feed, these elements enter into the food chain and cause health problems. Excessive use of inorganic fertilizer has harmful effects on crops like lodging of cereals and the low sugar content in sugar beet. Intensive agriculture together with haphazard use of irrigation water causes problems such as soil salinity and waterlogging. Use of poor-quality irrigation water also leads to an increase in salinity. Excessive use of canal water and saline irrigation water has led to a more salinized area in states like Punjab, Haryana, and Uttar Pradesh. Pesticide application in cultivated land might also have a certain toxic effect on living beings. Degradation of some pesticides takes a long time, and consumption of crops with pesticide residues adversely affects the biological system. An estimate showed that 60,000 tons of pesticides enter in India every year, out of which one-third is used for public health and two-thirds in agriculture (Aggarwal et al. 2009a, b; Yadav et al. 2018b). Pesticides harmfully affect soil by reducing soil microbial activity, inhibiting different processes in the nitrogen cycle, reducing earthworm population, and decreasing certain enzyme activities in soil. The soil is also a source of GHGs like CH4, CO2, and nitrous oxide (N2O), thereby directly affecting climate change. Continuous application of inorganic fertilizers causes deficiencies of many secondary and micronutrients.

Agricultural intensification causes a decrease in abundance and biomass of most groups of organisms which are the functional parts of the food web. Intensive farming though having a lot of advantage compared to the traditional farming severely affects the ecology and environment especially the soil. Species biodiversity decreases high-input agricultural practices?? (Gogoi et al. 2018). Biological species (like earthworms and arbuscular mycorrhizal fungi) which have restricted mobility and recolonization are greatly affected by intensive tillage practices. Not all functional or taxonomic groups or species are decreasing with tillage practices; some are even favored by tillage intensification, like bacteria and bacteria-feeding nematodes.

5.1.2 Conservation Agriculture: A Need and Goal

The term "CA" has newly been adopted by the Food and Agriculture Organization and defined as "CA" aims to conserve, improve and make more efficient use of natural resources through integrated management of available soil, water, and biological resources combined with external inputs. It contributes to environmental conservation and to enhanced and sustained agricultural production. It can also be referred to as resource efficient or resource effective agriculture. CA can give satisfactory returns and greater and persistent crop production and, at the same time, save the environment. Its goal is to reduce/discard the negative impact of traditional agricultural practices like intensive tillage, burning/removal of crop residues. Hereafter, CA (combined with external inputs) aims to save, and effective use of natural resources by integrated management of soil, biological resources and available water (Bhan and Behera 2014; Meena et al. 2017b). CA is based on good agronomic practices (GAP) which involves timely farm operations, quality seed use, and integrated nutrient, water, pest, and weed management (Kassam et al. 2009). The yield under CA system is at par with the conventional system which means farmers do not have to compromise with crop yield. Many researchers have considered CA as a base for sustainable agricultural production intensification (Kassam et al. 2009; Jat et al. 2013; Farooq and Siddique 2015; Yadav et al. 2017b). The goal of CA is to provide sustainable and cost-effective production system, climate change adaptation and mitigation strategies, and land degradation neutrality (Derpsch 2008). The adoption of CA will help to decrease production costs and alleviate threats to soil health, water quality, and biodiversity, and at the same time, CA causes an increase in crop productivity and resource use efficiencies (Midgley et al. 2015; Meena et al. 2018c). Agronomic and crop management practices should be followed for reducing GHG emissions (like CO2 and CH4) by decreasing tillage and residue burning and enhancing nitrogen use efficiency. Through the adoption of CA, the environment becomes more healthy and sustainable while maintaining environmental integrity and ecosystem services for the wider community because of reduced fossil fuel consumption, fewer pesticides, and other chemicals use (Bhan and Behera 2014; Meena et al. 2018b). CA is based on regulatory codes that can be universally applied, naturally ensuing in boosted SOC over time:

- To minimize soil disturbance for achieving sustainable production
- To maximize surface soil cover by dealing with crops, cover crops, pastures, and plus crop residues
- To stimulate biological activity by suitable crop rotations and cover crops and adapting integrated pest and nutrient management

Some of the distinguishing features of CA over conventional agriculture have been presented in Table 5.1 (Bhan and Behera 2014).

5.1.3 Conservation Agriculture: Status in India and World

CA production systems are used throughout the world. Right now, CA is followed on approximately 157 million ha arable land worldwide (https://en.wikipedia.org/wiki/Arable_land (1 Nov 2017)). Of the total area, 90% is in the USA, Brazil, Argentina, Canada, and Australia (Fig. 5.1). Various reports have shown that reported (Kertész and Madarász 2014; Friedrich et al. 2012) globally the increase in rate of CA adoption has become 7Mha/year as compared to the past millennium, and ever since 2008/2009, the rate has increased to 10 Mha/year (Kassam et al. 2009; Yadav et al. 2017c). In Asia, presently more than 10 Mha arable cropland are under CA system which is about 6.5% of the global CA area – mostly situated in China (65.4% of the total Asian CA area) followed by Kazakhstan (19%) and India (around 15%). CA practices are relatively new in Asia, and the large area is shared by India in the Indo-Gangetic Plain (IGP).

Subsequently, after 2008/2009, more number of countries are adopting and promoting CA, and the number has become 55 in 2013 which was 36 in 2008/2009 (Table 5.2). The global extent of CA in 2011 is around 125 Mha (Table 5.3).

Table 5.1 Few differentiating characteristics of conventional and conservation agriculture systems

Conventional agriculture	Conservation agriculture
Cultivation of land with the help of science and technology to govern nature	Minimum intervention with natural system
Disproportionate mechanical ploughing which causes soil erosion	Zero tillage or severely reduced tillage (biological tillage)
Higher wind and soil erosion	Little wind and soil erosion
Residue burning or removal from soil surface (bare surface)	Permanent retention of crop residues on surface
Worsening of soil physical, chemical and biological health and water infiltration and retention is low	Better soil physical, chemical, and biological health and higher water infiltration
Use of ex situ FYM/composts	Use of in situ organics/composts
Green manures are incorporated in the soil	Surface retention through brown manuring/cover crops
Production cost and diesel use are more	Production cost and diesel used reduces drastically
Loss of organic matter is more because of rapid oxidation	Buildup of organic matter is more
Kills weeds already present in soil but also encourages more weed seeds to germinate	Weeds problem in the initial years of adoption but decrease with time
Repeated use of heavy farm machinery causes more soil compaction	Controlled traffic in certain passage of the field causes no compaction in crop area
Yield can be lower where planting delayed	Yields are at per with CT, but higher production is planting and is done timely
More variation of soil surface temperature	Moderation of soil surface temperature

Modified from Bhan and Behera (2014)

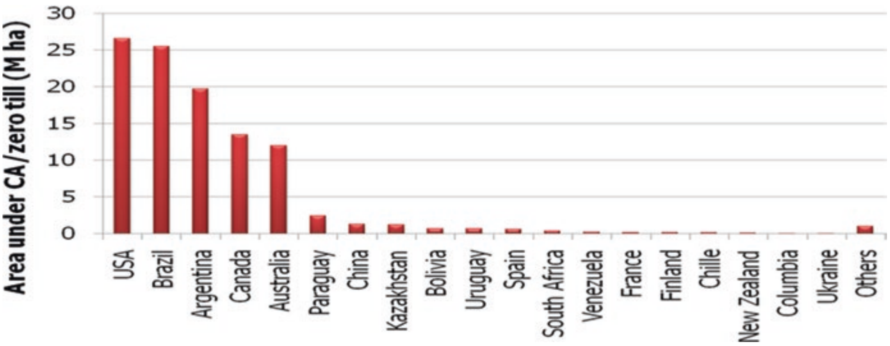

Fig. 5.1 Worldwide area under conservation agriculture [Adopted from Pathak and Singh (2015) (Data source: Derpsch and Friedrich 2009)]

5.1.4 Different Components and Practices of CA

CA farming systems are designed to reduce soil erosion and land degradation through residue cover, moderate soil hydrothermal regimes and conserve moisture, increase OM in soil and improve soil structure and fertility, improve soil health through increased soil biodiversity, reduce GHG emissions, reduce fuel and labor costs, achieve viable and sustainable productivity, improve yields on long-term basis, and reduce vulnerability to climate change. CA as a modern agricultural production technique enables the farming community in several parts of the globe to accomplish the sustainable agricultural production goal. Different components and practices followed (Fig. 5.2) under CA are as follows.

5.1.4.1 Soil Management

The fundamental parameters to sustain agricultural productivity are the physical and chemical properties and biological activity of soil, including the spatial arrangement of soil components that determine their complexity, soil health, and fertility. Soil fertility could be improved by minimizing losses of soil, nutrients, and agrochemicals from erosion, runoff, and leaching into surface- or groundwater. Agricultural practices should consider the following:

- Setting up of a detailed knowledge base regarding the nature, properties, distribution, and potential uses of soils of the farm
- Avoiding mechanical disturbance of the soil to the extent possible
- Avoiding soil compaction beyond the elasticity limit of the soil
- Maintaining balanced nutrient levels in soils
- Avoiding contamination with agrochemicals, organic and inorganic fertilizers, and other chemicals by applying right quantities, application methods, and timing to as per the requirements of soil and environment

Table 5.2 Extent of adoption of CA worldwide by country in the 2008/2009 and 2013 updates

Country	CA area '000 ha 2008/2009 update	CA area '000 ha 2013 update
USA	26,500.00	35,613.00
Brazil	25,502.00	31,811.00
Argentina	19,719.00	29,181.00
Canada	13,481.00	18,313.00
Australia	12,000.00	17,695.00
China	1330.00	6.670.00
Russia	–	4500.00
Paraguay	2400.00	3000.00
Kazakhstan	1300.00	2000.00
India	–	1500.00
Uruguay	655.10	1072.00
Spain	650.00	792.00
Bolivia	706.00	706.00
Ukraine	100.00	700.00
Italy	80.00	380.00
South Africa	368.00	368.00
Zimbabwe	15.00	332.00
Venezuela	300.00	300.00
Finland	200.00	200.00
France	200.00	200.00
Zambia	40.00	200.00
Germany	354.00	200.00
Chile	180.00	180.00
New Zealand	162.00	162.00
Mozambique	9.00	152.00
United Kingdom	24.00	150.00
Colombia	102.00	127.00
Malawi	–	65.00
Turkey	–	45.00
Mexico	22.80	41.00
Moldova	–	40.00
Slovakia	10.00	35.00
Kenya	33.10	33.10
Portugal	25.00	32.00
Ghana	–	30.00
Syria	–	30.00
Tanzania	–	25.00
Greece	–	24.00
DPR Korea	–	23.00
Switzerland	9.00	17.00
Iraq	–	15.00
Sudan	10.00	10.00
Tunisia	6.00	8.00
Madagascar	–	6.00

(continued)

Table 5.2 (continued)

Country	CA area ‘000 ha 2008/2009 update	CA area ‘000 ha 2013 update
Hungary	8.00	5.00
Morocco	4.00	4.00
Uzbekistan	–	2.45
Lesotho	0.13	2.00
Azerbaijan	–	1.30
Lebanon	–	1.20
Kyrgyzstan	–	0.70
Netherlands	–	0.50
Namibia	–	0.34
Belgium	–	0.27
Ireland	0.10	0.20
Total	**106,505.23**	**156,980.96**
% difference		**47.39**

Source: AQUATSTAT: www.fao/org.ag/ca/6c.html

Managing a Permanent Soil Cover

CA systems involve crop rotations (2–3 years period), soil surface cover management, and other farm activities. The type of cover crop and its rotations and management should make sure that it could satisfactorily meet all needs of permanent soil cover, human and livestock feeding, fibers, etc. In CA, the use of agrochemicals like desiccants and herbicides should be curtailed.

Multipurpose cover crops should be grown through appropriate technologies. A crop like Indian hemp (*Crotalaria juncea* L.) should be selected as a cover crop as it is very effective in nematode control and, at the same time, it helps in nitrogen fixation, organic carbon addition, and soil fertility improvement. The cover crops selected for an area should be socioeconomically accessible to farmers. Leftover residues of cover crops help in improving several soil properties like water conservation through more infiltration and reduced evaporation (Unger et al. 1998). Crop residue on the soil surface can help in improving soil quality, nitrogen use efficiency (NUE) and recovery and also crop yield. Surface mulch also helps in reducing evaporation losses of water and moderating soil hydrothermal regimes (Aggarwal et al. 2009a, b). Studies reported that surface residue from cover crop stimulates biological activity and improves nitrogen mineralization in surface soil layer (Dao 1993; Hatfield and Prueger 1996) and accumulates OM in soil profile (Alvear et al. 2005; Varma et al. 2017), and this effect is amplified when combined with no-tillage (NT).

Minimum Soil Disturbance: Zero Tillage

Depending on the soil and climatic conditions, seed characteristics, and soil cover properties, the seed can be sown by direct seeding, direct planting, or broadcasting. Before adopting ZT in an area, mechanical impedance like hardpan and surface crusting or compaction should be removed and laser land leveling should be practiced. Chemical limitations like salinity, sodicity, and acidity should be controlled by applying suitable amendments like lime, gypsum, or OM. The ZT along with the

Table 5.3 Extent of adoption of conservation agriculture worldwide (countries with >100,000 ha)

Country	CA area (ha)
USA	26,500,000
Argentina	25,553,000
Brazil	25,502,000
Australia	17,000,000
Canada	13,481,000
Russia	4500,000
China	3,100,000
Paraguay	2400,000
Kazakhstan	1,600,000
Bolivia	706,000
Uruguay	655,100
Spain	650,000
Ukraine	600,000
South Africa	368,000
Venezuela	300,000
France	200,000
Zambia	200,000
Chile	180,000
New Zealand	162,000
Finland	160,000
Mozambique	152,000
United Kingdom	150,000
Zimbabwe	139,300
Colombia	127,000
Others	409,440
Total	**124,794,840**

FAO (2011c)

normal rate of crop residue led to better soil structure and aggregation, and this improvement in soil is additive in nature.

ZT along with crop residue retention aids in removing surface soil crusting, improving soil hydraulic properties like infiltration and hydraulic conductivity, and reducing increased water runoff which altogether helps in getting higher crop yield than conventionally tilled soils. Also, the crop residue either anchored in soil or loose on surface guards the soil from the erosive action of wind (Michels et al. 1995). Conventional tillage and current intensive agricultural practices cause a rapid reduction in OM content in soil due to increased oxidation over time, leading to soil degradation and loss of soil biological fertility and resilience (Lal 1992). In contrast, ZT along with permanent soil cover helps in a buildup of OC in soil profile by minimizing SOM losses, an encouraging strategy to sustain or even rise in soil carbon and nitrogen stocks (Bayer et al. 2000; Meena et al. 2017c).

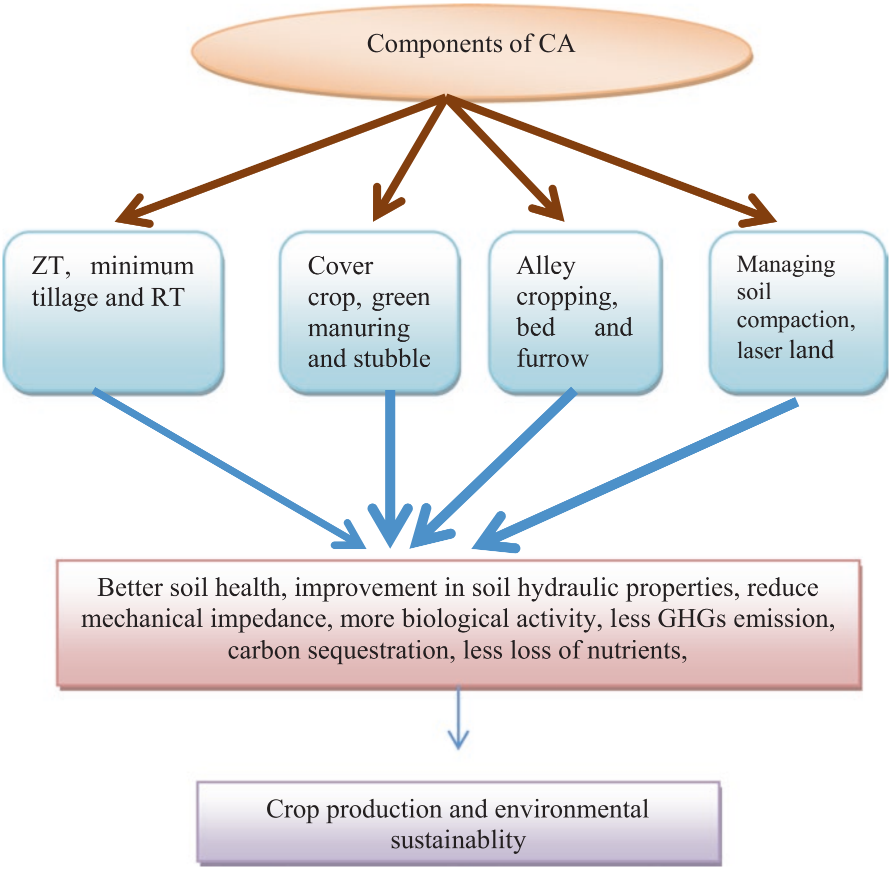

Fig. 5.2 Different components and practices of CA

5.1.4.2 Pest, Weed, and Fertility Management

Managing of pest, weed, and soil fertility is a very serious issue while carrying out CA experiment. To make a new balance between the organisms and the farm ecosystems – pests and beneficial organisms, crops, and, weeds – the use of synthetic pesticides herbicides and other chemicals should be minimized.

Pest Management

In CA system, known or unknown pests occurred at the initial period may be controlled through chemicals. But suitable crop rotations and proper use of cover crops could help in interrupting the infection chain between the crops, thus reducing the chemical use. In CA, integrated pest management (IPM) technologies are the main aspects for controlling pest and disease occurrences (Khan et al. 2011). So, proper knowledge and training regarding IPM is very much required for implementing CA.

Weed Management

In the early years, synthetic herbicides may be necessary but should be used very carefully and minimally so that it does not affect the soil health. Mulch cover and cover crops, crop rotations, desiccants, and herbicides are the technologies to control weeds (Chauhan et al. 2012). Mechanical weed control through rolling, cutting, or breaking can also be applied. Biological weed control may be very effective through appropriate choice of cover crops.

Fertility Management

Before and during the implementation of CA soil limitations, such as acidity, salinity, or toxicity, problems must be addressed. Judicious choice of crops and cover crops play a key role in soil fertility management. Farmers with poor resources or access to mineral fertilizers could make the use of integration of livestock in the system which could be a promising solution (FAO 2012). The use of organic and mineral fertilizers may be necessary. Appropriate application can be done with combined tools for direct seeding-fertilization.

5.1.4.3 Avoid Burning of Crop Residues

To maintain permanent cover on soil surface, residue of previous crop should not either be burnt or removed. Leftover residue on soil surface helps to protect the soil from erosion, to build up OM in soil. Residue burning which caused rapid depletion of SOM and available soil nutrients can be minimized if crop residues are used for maintaining soil cover (Mandal et al. 2004; Layek et al. 2018).

5.1.4.4 Direct Planting of Crop Seeds

Raising crops without making seedbed mechanically and disturbing soil at minimum level is known as direct planting/seeding (i.e. Maize and beans, etc.). In CA, direct seeding is considered synonymous with ZT, no-tillage (NT), NT farming, direct drilling, etc. (Thierfelder and Wall 2010). On the other hand, seeding is done in case of small grain cereals like barley and wheat through continuous placement of seeds in soil. Direct seeding is done with seed driller. The equipment enters into the soil surface, makes a seeding slot, and put the seeds into that slot (Derpsch 2003). The seed slot size and the associated disturbances to the soil should be minimum. In ZT/NT, for seeding or planting of seeds, land is prepared through cutting or rolling the weeds, leftover crop residues, or cover crops. Then, herbicides are spread for controlling weeds and seeding is done straightway through the mulch. At the time of seeding or planting, the soil is covered totally or partly with crop residues. Dumanski et al. (2006) reported that crop diversification is necessary for food supply to the soil microorganism, and at the same time extensive root system helps in extracting nutrients from deeper soil layers which remains available for successive crops in the season.

5.1.4.5 Controlled in Field Traffic

In the conventional system of farming, heavy farm machineries are passed normally across a field at random. The repeated movement of heavy equipment in the field causes exposure of soil which leads to structural degradation and subsoil compaction. Available literature and many experimental results showed that soil compaction due to repeated traffic in field decreases infiltration rate, hydraulic conductivity, total porosity, and aeration status of soil but increases bulk density (BD) and impedance to root growth. Controlled traffic farming (CTF) deals with the management of soil compaction (Junda et al. 2000). CTF helps in passing the heavy equipment through a narrow passage in the field and leaves the maximum undisturbed area for crop growing. In CTF, machinery tracks are prepared by using the least possible area. CTF reduces both fuel and labor cost. Certain environmental benefits of CTF includes higher nutrient use efficiency, reduced runoff and associated soil erosion, less emission of GHGs, etc. (Gasso et al. 2013). It is one of the promising components of conservation agriculture as it has benefits such as better seedbed, improved soil structure, improved water storage, and increased potential and accuracy of global positioning systems (GPS).

5.1.5 Soil Physical Health Under CA

Keeping crop residue on the surface of soil helps in improving soil health and total resource utilization. CA practices can improve the water and nutrient use by enhancing nutrient availability and balances, infiltration, and retention of water in soils, through reducing evaporation losses and augmenting the ground- and surface water availability and quality (Sharma et al. 2005; Varma et al. 2017b). Better SOM, more soil aggregation, higher moisture conservation, improved porosity and pore size distribution, water infiltration and redistribution, and favorable bulk density (BD) are few factors that are responsible for greater crop productivity in CA treatments (Jalota et al. 2008). A study conducted by Bhattacharyya et al. (2013) reported that after 4 years of experiment, plots under ZT with permanent bed had 5% higher soil BD than conventional plots (1.51 Mg m3 for 0–5 cm soil depth. Fabrizzi et al. (2005) and Gantzer and Blake (1978) have reported higher BD and penetration resistance (PR) values under ZT as compared to CT. In contrast, Anikwe and Ubochi (2007) informed that soil coverage with residue by NT systems showed no significant variation in soil properties, particularly in the few centimeters of the upper soil layer. Voorhees and Lindstrom (1984) revealed that porosity, BD, and mean weight diameter (MWD) of soil aggregates improved from the time of start of a tillage trial in both CA and conventional tillage. Though Bautista et al. (1996) reported that ZT with residue decreased bulk density (BD) considerably, Sayre and Hobbs (2004) found higher BD in ZT along with residue retention but greater infiltration rate because of more stable soil structures (high MWD of aggregates) due to more earthworm activities.

The CA practices like raised bed system boost WUE by controlling soil evaporation and lessening erosion losses improve the physical environment of soil and hasten root propagation (Ahmad et al. 2009) and moderate soil temperature (Aggarwal et al. 2009a, b). Several studies reported the usefulness of bed planting system (one of the CA technologies) over the conventional planting system because of its reduced mechanical impedance, better root growth, greater nutrient, and WUEs (Aggarwal et al. 2009a, b). Aggarwal et al. (2017) reported a greater experimentally measured values of saturated hydraulic conductivity (Ksat) in CT plots as compared to ZT plots because CT plot had more porosity and lower BDs in 0–30 cm soil depth.

Kargas et al. (2012) witnessed that ZT plots preserved additional water than CT plots. They also described that in ZT, soil pore geometry improved because storage pores of 0.5–50 mm size and transmission pores of 50–500 mm size increase. They also found that greater microporosity in ZT caused an increase in soil water content and subsequently plant available water in 0–10 cm soil. Results of a 6-year CA experiment showed that 25% more water was conserved in ZT plot and also observed significantly higher WUE in ZT as compared to CT and reduced tillage (RT) (Su et al. 2007). Rasmussen (1999) noticed that high soil water content (SWC) and retention of crop residue on the surface in CA resulted in reduced evaporation loss and subsequently reduced soil temperature fluctuation. In ZT along with residue, evapotranspiration (ET) was more because of higher leaf area (Aggarwal et al. 2017). In CA, soil water storage is more and extended up to deeper soil layer because of less exposure of soil to water loss by evaporation (Su et al. 2007). Stable isotope study conducted by Busari et al. (2015) revealed more accumulation of stable isotopes δ18O and δD adjacent to the soil surface of CT plot as compared to ZT plots which indicated more evaporation loss from CT plots. Liakatas et al. (1986) consider temperature is probably the utmost significant factor among the various environmental factors. They also reported the insulating effect of mulch in altering soil hydrothermal regimes which affected crop growth, establishment, and productivity. Mulch helps to attain greater soil temperatures than the uncovered ridges (Graefe 2005; Meena and Yadav 2014). Pramanik et al. (2015) observed the highest soil temperature under charcoal + compost-treated plot, followed by no manure plot, and lowest soil temperature was observed under green manure-treated plot. The soil temperature of transparent polythene-treated plot was 5–6 °C more over no polythene plot, but this variation lessened down with depth. A similar type of result was also previously observed by Wilson and Jasa (2007).

5.1.6 Soil Organic Carbon Dynamics Under CA

SOC pool is a very vital factor in the entire ecosystem including agriculture. Natural resource base valuation depends on the amount of SOC present in the system. Effect of management practices on soil health and ecosystem services are also determined based on SOC present in the soil. SOM is a mixture of undecomposed or decomposed organic materials, having different durations of processing time by soil organisms. SOM may be alive or dead, dying, or partially decayed. Living OM includes plant parts and roots and different macro- and microorganism like insects, earthworms, fungi, protozoa, and bacteria. SOM contains 50–58% of carbon as the principal constituent. Therefore, the terms SOM and SOC are used interchangeably. Less than 10% of SOM is living but plays a very significant role in nutrient recycling, decomposition of OM, soil structural stability and aggregate formation, plant rhizosphere modification, and ecological resilience by influencing underground biodiversity. Nonliving part of SOM is characterized in a diverse way as per the compound's complexity. In 1 m soil depth, approximately 1600 Pg C is stored as organic carbon. In addition to this, around 700 Pg C is deposited in the soil as inorganic carbon like carbonate minerals. A very vital indicator of soil quality is SOC. The soil organic carbon under CA practices has been known to maintain many soil health parameters. In soil, SOC acts as a binding agent. Mineral particles are bound together by SOC and form water-stable aggregates. Formation of water-stable aggregate improves the soil structure and subsequently enhances infiltration and water storage in the soil. Higher negative charges of SOC help in the retention of positively charged ions like Al3+, Fe+2, Fe+3, Ca + 2, Mg + 2, and NH4 + -N, enhance the availability of phosphors and metal dissolution, and decrease micronutrient losses and toxicity of chemicals. SOC in soil is the prime source of metabolic energy which helps in driving biological processes. Use of excessive synthetic fertilizers has caused the depletion of SOC from the soil. In CT, because of repeated tillage, SOC is depleted at a very faster rate due to rapid oxidation. If the SOC of soil is increased, then non-nutrient characteristics of SOM can be improved. In CA, over a long time, SOC is distributed vertically in well-stratified layers. From the ecological point of view, surface soil should be rich of SOC because it gets the maximum amount of synthetic fertilizers and pesticides and it has to bear destructive actions of raindrops and further external factors like speedy winds and floods. In soils with more SOC, plant roots and soil biota modify the soil matrix so that the soil becomes stable with permanent network of passages (biopores) which helps in more infiltration of water into the soil. As, in CA, soil is being disturbed minimally and the surface remains cover with crop residue, the SOC pool is built up in soil profile with time (Figs. 5.3 and 5.4). In CA, SOC pool is mainly built up in surface soil because the crop residue remained in surface decomposes with time after getting water through rainfall or irrigation. If sufficient synthetic fertilizers are applied in nutrient-deficient soil, a poor structure with low OM soil, crops can grow but each type of soil should maintain a suitable range of SOC tock because SOC has a very vital role in producing food, fiber, feed, and fuel. Agricultural management practices like ZT along with crop residue can reduce erosion rate as well as SOC balance in the soil very fast (Roose and Barthes 2001; Six et al. 2002; Nandwa 2001). Several studies have shown rapid mineralization after continuous monocropping and land clearing which decreased SOC by 30% (Gregorich et al. 1998; Nandwa 2001). Also, 4–20 times greater erosion has been reported from the crop field grown under intensive tillage than natural soils (Roose and Barthes 2001). In

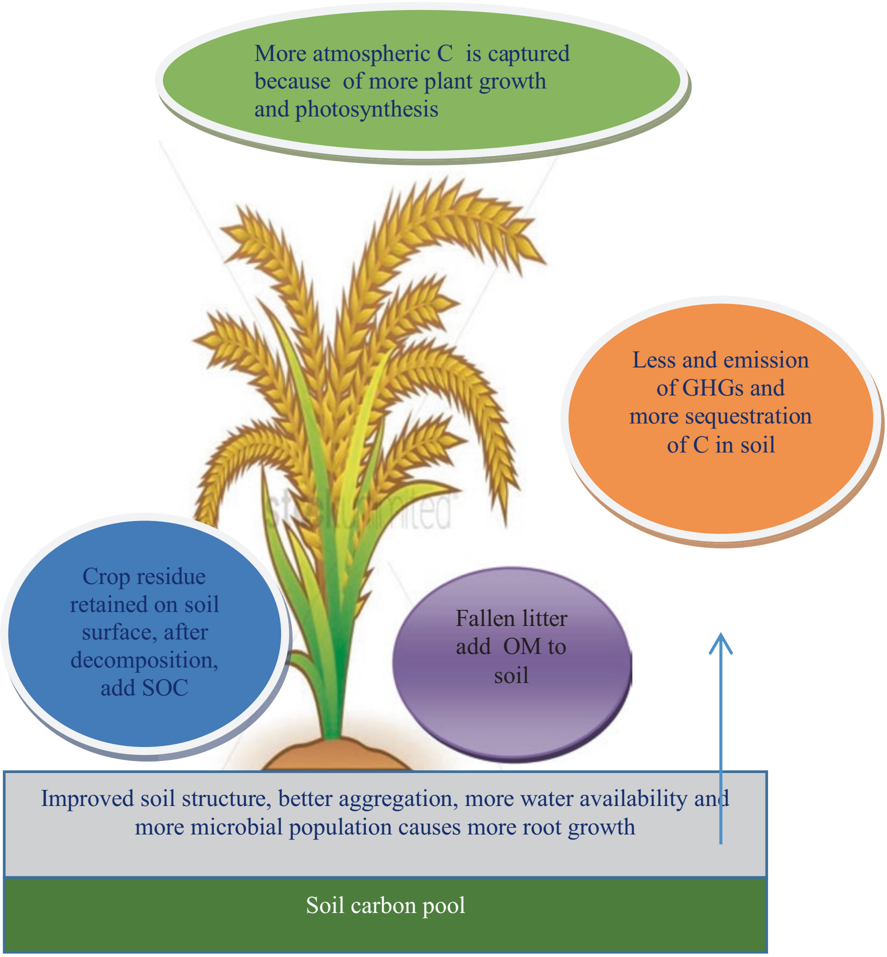

Fig. 5.3 Mechanism of more carbon addition to soil in CA

ZT, lower SOC loss is observed as the soils are disturbed less. Several studies have reported more accumulation of SOC when crop rotations and intercropping are done. When crop residues are used as mulch, it helps in moderating soil temperature, maintaining good soil structure and higher infiltration rate, and enhancing macro- and microfauna and flora activities (Roose and Barthes 2001; Meena and Yadav 2015). When synthetic fertilizers are applied without any organic mineral sources, then it causes loss of SOC. For enhancing SOM or SOC level in the soil, practices for saving SOC loss from soil and adding SOC to the soil directly or indirectly or practices which will warrant efficient use of SOM at different scale should be followed.

Fig. 5.4 More residue addition in CA leads to more SOC

5.1.7 Future Perspectives and Conclusions

The feasibility of CA in different regions of the world is constrained by biophysical and socioeconomic conditions. CA needs better knowledge of the system, and implementation of CA should be as per the site and farmer's condition. Totally different sets (from traditional tillage-based cropping system) of crop management practices are required for adaptation of CA. New techniques for seeding, fertilization, crop residue management, tackling weed problem, crop harvest, and postharvest management are very important for successful adaption of CA. Convincing the farmers through evidence that crop yields without tillage operation is the most vital task in motivating the farmers for adopting CA. Extension workers can play a role in providing sufficient knowledge and convincing the farmers regarding the superiority of each element of CA on crop yield. Farmers know the fertilization effect on crop yield, but the effects of ZT and/or crop residue maintenance on the soil surface and the combined effect of these two are comparatively unfamiliar and little assumed. The benefits of each element of CA are as well very tough to distinct as the maximum of the profits of the systems gets high when numerous constituents are combined together. The spread of CA depends on the farming community as they have to change their mindset up.

CA signifies the essential constituents of a new substitute paradigm of the twenty-first century and needs a vital modification in the production system. CA is currently recognized internationally as the utmost significant technologies having the potential to decrease the influences of intensive agriculture, increase and look after the natural resource, and regulate carbon dioxide productions. Policy makers and scientists' community should be fully convinced about the long-term social, economic, and environmental benefits of CA. It can help in climate change adaptation, by enhancing system resilience and therefore making the system less susceptible to climatic aberrations, and improved SOM, soil structure, and water storage which helps in reducing flood and erosion and drought effect, providing sustained yield, and reducing greenhouse gas emission. CA can be adopted as an emerging technology because of efficient residue management, ZT, and well-organized management of inputs.

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Legumes for Sustainable Soil and Crop Management

6

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Abstract

The climatic variations and swiftly increasing the world's population are crucial drivers of universal famines and lead to the stern food insecurity. These factors affect all the magnitudes of food collateral, such as food accessibility, consumption, reliability, and constancy, and also strengthen additional calamities allied with health concerns of plants, animals, and environment. Although applications of agrochemicals to the soil largely contributed to increased food production, extensive use of these leads to the nutrient disparity and environmental hazards resulting in considerable economic losses. Consequently, it is utmost important to manage the application of agrochemicals with the aim of increased food production in environmental as well as economical unthreatened manner. Legumes have a great potential to enhance crop diversity as well as productivity and to reduce dependence on exterior inputs as legumes are well known for their illustrious capabilities such as nitrogen (N) fixation by biological means, increase in soil organic matter (SOM), efficient roles in nutrient and water retention, and improvement in soil properties which contribute to recover soil health. These manifold abilities of legumes make them potential candidates for management of agriculture in a sustainable way. The upshots of sustainable agriculture can be optimistic for higher food production and to ensure future food availability in an eco-friendly manner by reducing the usage of agrochemicals and maintaining the nutrient balances in the soil.

Keywords
Biocontrol · Chemical fertilizers · Green manure · Legumes · Nitrogen fixation · Soil health · Sustainability

Abbreviations

(BCAs)	Biological control agents
AM	Arbuscular mycorrhiza
BNF	Biological nitrogen fixation
CO_2	Carbon dioxide
FAO	Food and Agriculture Organization
FGLTs	Fast-growing legume trees
IPMPs	Integrated pest management practices
N	Nitrogen
NO_2	Nitrogen dioxide
NO_3^-	Nitrate
NUE	Nitrogen use efficiency
OF	Organic farming
P	Phosphorous
SOC	Soil organic carbon
SOM	Soil organic matter
US	United States

6.1 Introduction

The scarcity of food is still a critical issue since World War II as an agricultural system is lacking advanced and efficient agricultural and engineering technologies (Coles et al. 2016; Yadav et al. 2018b). With the passage of time, as the agricultural system became mechanized with modern agricultural technologies to increase the crop productivity, the cumulative increase in food production has enhanced by 145% (Pretty 2008; Meena et al. 2015d). At the same period of time, the world's population increased very fastly and also estimated to reach up to 8.1 billion in 2025 and further to 9.6 billion in 2050 and 10.9 billion by the end of the twenty-first century (United Nations: Key Findings and Advance Tables 2013). Due to this enthusiastic increase in population, the blueprint of food utilization has been changed leaving the world with limited food reservoirs. As a consequence, the world is facing a state of hunger, and the number of underfed people has increased to 821 million in 2017 which was nearly 804 million in 2016 (FAO 2018). Therefore, we are facing a big challenge, that is, how to feed this massively increasing malnourished population with limited availability of food resources.

To meet the enormous food demands of a growing population, food production needs to be increased rapidly (Hasler et al. 2017; Ashoka et al. 2017). For an intensive increase in food production, presently the conventional agricultural practices are highly dependent on the greater use of chemical fertilizers (Stehfest and Bouwman 2006; Meena and Meena 2017). In developing countries, farmers make use of chemical fertilizers extensively to their croplands in order to get increased crop productivity. The amplified food production can be assigned to 6.9- and 3.5-fold increase in nitrogen (N) and phosphorous (P) fertilization, respectively (Rahman and Zhang 2018; Kakraliya et al. 2018), and by having a critical vision on present-day agricultural practices, it is estimated that additional 40 and 20 million metric tons of N and P fertilizers will be required by the end of 2040, correspondingly (Vance 2001; Kumar et al. 2017b). The disproportionate uses of these chemical fertilizers have detrimental effects on the economy of a country, society, and environment as these are very costly, associated with several health risks to humans, animals, and soil. The uncontrolled application of N fertilizers results in leaching and consequent mixing with soil water which alters soil and water chemistry leading to unfavorable effects on ecosystem. The excessive utilization of these fertilizers also causes depletion of nonrenewable energy resources as industrial scale manufacturing of these fertilizers exploit natural gas and coal and additionally, responsible for the production of greenhouse gases, viz. carbon dioxide (CO2) and nitrous oxide (NO2) that markedly contribute to air pollution causing immense damage to the environment (Parikh et al. 2009; Liu et al. 2011; Liu et al. 2013; Xiao-qiang et al. 2018; Meena and Yadav 2015).

Crop production comes across rigorous global economic losses by the attack of different kinds of phytopathogens which results in about 30% loss of crop productivity annually (Nehl et al. 1996); it's costing ~416 million US dollars. In order to overcome the economic losses, pesticides are used to control the growth of disease-causing microbes. Therefore, besides fertilizers, pesticides are other chemicals being used indiscriminately which impart a great peril to the environment in terms of ill effects on natural microflora, phytotoxicity, and persistence in the environment for a considerable period of time (Bhattacharyya et al. 2017; Yadav et al. 2018a). As these chemicals deteriorate the fertility of the soil and pollute the environment resulting in degradation of natural resources, their food production capability for future generations decreases. Hence, this called an immense need of alternative strategies to nourish the crops with appropriate nutrients, to control production losses due to biotic factors, and to improve soil qualities (Franco-Correa et al. 2010; Rani et al. 2018a, b; Buragohain et al. 2017). The term “sustainability” stands for “the ability to be maintained at a certain rate or level” or “avoidance of the depletion of natural resources in order to maintain an ecological balance” (Oxford Living Dictionaries) and goes well with the maintenance of good soil health and keeping it fertile for future generations.

Legumes fit in Leguminosae family which embraces 800 genera and 20,000 species and represents the third largest family among flowering plants (Stagnari et al. 2017; Meena et al. 2016a). In the view of nutritional value, legumes are second after the cereals. Legumes, being a rich source of proteins, are considered as an important economic dietary component for poor people in developing countries. Also, legumes have forage value for the use of animals as a nutrient supplement. In addition to these nutritional uses, legumes are used for making doughnuts, bread, various kinds of snacks, etc. (Meena and Lal 2018; Datta et al. 2017a). Overwhelmingly, legumes have multiuses and can be utilized as either unswervingly or in a processed manner (Berihun and Molla 2017; Yadav et al. 2017a). Besides nutritional importance, legumes have a very wide range of applications in maintaining sustainable agriculture (Peix et al. 2014; Rubiales and Mikic 2015; Meena et al. 2018a, b, c) (Fig. 6.1) which incorporates three foremost objectives, i.e., environmental health, economic prosperity, and social evenhandedness.

Legume-based farming in place of cereal-based aids the soil with essential nutrients which in turn promote crop yield, stability, and wholesomeness of food system (Hauggaard-Nielsen et al. 2007; Dhakal et al. 2015). At the same time, conventional agricultural system needs to shift toward organic and more sustainable crop production. So, in that case, legume farming or legume-cereal intercropping is considered as the chief and prime component as it improves the soil health by aiding with nutrients and preventing destruction of soil properties arising from monoculture farming.

6.2 Improvement in Soil Health

Soil organic cache and soil properties get deteriorated as a consequence of monoculture farming and due to extensive use of agrochemicals. Pesticides are mainly grouped into four major categories depending upon their target pests, i.e., insecticides, herbicides, fungicides, and rodenticides. Pesticides are associated with non-target impacts to a great extent and negatively influence the soil ecosystem as well as human beings (Klaassen and Watkins 2003; Yadav et al. 2017b).

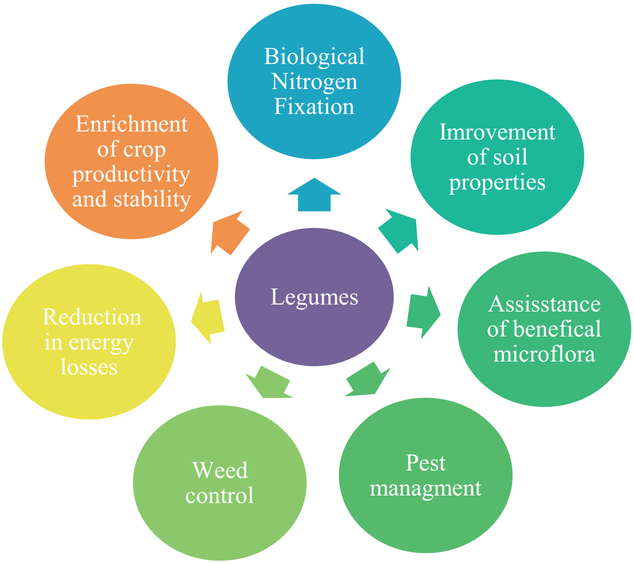

Fig. 6.1 Applications of legumes aiding soil health and sustainability

The espousal of integrated pest management practices (IPMPs) and organic farming (OF) with an endeavor to remediate polluted soil is the immense need of a current agricultural system to manage soil health sustainably (Lal 2011; Meena et al. 2016b). Legume farming is a well-known approach to sustain soil health by means of BNF (Hauggaard-Nielsen et al. 2007), P solubilization/mobilization (Kamal et al. 2014; Kumar et al. 2018a, b) and absorption of deeper soil nutrients by their deeper/taproot system resulting in trimming down the need of fertilizers and also reducing the risks associated with pesticides as legumes has the flair to modulate rhizospheric microflora which in turn, helps to suppress phytopathogens in soil (Sanderson et al. 2004; Kumar et al. 2018a) and abet increase in crop yield and its stability (Bybee-Finley et al. 2016), which make it an imperative tread for sustainable agroecosystem.

6.2.1 Perspective of Nitrogen Fixation

The massive demands of food for the vast population in developing countries are usually fulfilled by application of synthetic fertilizers (for nutrient supply, especially nitrogenous fertilizers), herbicides, and other pesticides (for suppression/killing off weeds and pests) (Andrews et al. 2010). Due to extensive application of N fertilizers worldwide, intensification in the expenditure of chemical N fertilizers has reached to about 104 million tons (Tg) in 2006 from 11.6 Tg in 1961 (Mulvaney et al. 2009) and also expected to increase further to a very great extent in future. For manufacturing of inorganic N fertilizers, a large amount of nonrenewable energy is devoured to carry out N2 reduction. The robust avowals of dwindling in biodiversity in agricultural systems and instinctive systems assaulted by agricultural practices have been coupled with intensive use of chemical fertilizers (Aerts et al. 2003; Raven and Taylor 2003; Varma et al. 2017a). These tribulations associated with extensive use of chemical N fertilizers have therefore directed the farmers to look for substitutive proposals of farming to deal with inadequate soil nutrients (Andrews et al. 2003; Raven et al. 2004; Dadhich and Meena 2014).

The more proficient consumption of N to ensure increased food production and to reduce hazards to ecosystems ought to be a strategic goal for managing nutrient supply to the soil and agricultural sustainability (Goulding et al. 2007; Verma et al. 2015c). Beside chemical fertilizers, additional sources for soil enrichment with N are also available. The trivial ones include N accumulation form atmosphere as ammonia and/or oxides of N and application of cast-off sewage slush to plowed landscape, and the foremost one includes N fixation by biological processes (Hirel et al. 2011; Gogoi et al. 2018). Legumes are well known to fix atmospheric N2, and their cultivation reduce the requirements of chemical N fertilizers up to a significant level. Gram-negative rhizobia march into the roots of leguminous plants by making a thread-like structure and create polymorphic structures on plant roots which are the main site of atmospheric N fixation. The fixed N is then bestowed to host plants making them able to grow in the dearth of exterior N supply (Bardos et al. 2011; Meena et al. 2015a).

Moreover, if a fraction of this biologically fixed N becomes accessible to the next crop, cultivation of legumes plays a very striking role in decreasing the demands of chemical N fertilizers (Crozat and Fustec 2006; Dadhich et al. 2015). Furthermore, legumes play an imperative role in the improved establishment of a mycorrhizal symbiotic relationship with crop roots and also facilitate mycorrhizal interactions with bacterial N fixers, thereby influencing consumption of inorganic N fertilizers (Wang et al. 2011). Therefore, legumes represent an economic as well as eco-friendly approach of N supply to the soil and thus symbolize their potential to use as cover crops to replenish nutritionally exhausted soils.

6.2.2 Reduced Requirements of Chemical Fertilizers

The organic muck and legumes were formerly used to deal with constrictions of soil organic carbon (SOC) and N management which has directed toward chemical fertilizers due to increasing food insecurity (Hoang and Alauddin 2010; Meena and Yadav 2014). The quantities of chemical N fertilizers application to the soil have increased approximately threefold higher with respect to productivity enhancement (Tilman et al. 2002), indicating piercingly decrease in nitrogen use efficiency (NUE) by plants and representing loss of a significant amount of N in soil by means of leaching (Asghari and Cavagnaro 2011; Datta et al. 2017b).

The rhizosphere is a locale around the plant roots where colossal microbiological tricks occur. A number of microbes have potential to metabolize the residual N which is not taken up by the plants and accomplished to enrich soil productiveness.

The biological N fixation represents a vital resource of N in agroecosystem which has been anticipated to be approximately 122 Tg year-1 (Hirel et al. 2011; Layek et al. 2018). The principal representatives of N fixation are rhizobia found in mutually assisted relationships with legumes. The exudates secreted by plant roots are engaged in proliferation of microflora in root vicinity by acting as nutrients for their growth and development processes (Hinsinger et al. 2009). The proliferated microflora in turn aids in nutrient acquirement and retrieving soil fruitfulness. The enzymatic activities in the soil are unswervingly allied with a microbial population in the soil. As legumes cropping increases microflora populations in soil, it plays a key role in enhancing soil enzymatic potential (Roldan et al. 2003; Meena et al. 2015c). The enhanced enzymatic activities are associated with degradation of organic residues in soil aiding soil nutrient reservoirs. Therefore, legume farming aids in diminishing inorganic N fertilizer inputs which advance ecological agricultural approaches to improve crop yield and oppose environmental pollution.

6.2.3 Improved Nitrogen and Phosphorus Sustainability

The net application of inorganic fertilizers to the soil is commonly approximated devoid of deliberation of N inputs by biological process and plant roots themselves which have been anticipated approximately 91 kg N ha^{-1} in lupine (*Lupinus angustifolius*) (Russell and Fillery 1996) and must not be overlooked. The increased addition of N to the soil can escort to enhanced N losses via leaching and thereby does not essentially reveal the strengthening of soil N pool. Legume farming can reinforce the soil N pool if the quantity of fixed N is greater than the N taken away at the time of harvesting in the form of grains and leftover stubbles/stover.

Besides N, another imperative element for plant growth and development processes is P, whose deficiency leads to a great reduction of photosynthesis rate by means of destructive consequences on leaf section growth and thereby affects photosynthetic capability per unit leaf area (Chaudhary et al. 2008). As aerial metabolic and progressive events of plants are strongly linked with symbiotic associations of plant roots with rhizobacteria, the harmful effects of P deficiency are expected to have severe insinuations on the development and proper working of nodules as biological nitrogen fixation (BNF) is an extremely energy-entailing procedure (Sulieman and Tran 2015). In contrast to N, inorganic P reserves are nonrenewable and toward depletion. Consequently, development of legume cultivars having efficient N fixing capability in P-deficient conditions may possibly have tremendous importance in the enhancement of soil health and overall sustainability.

Being crucial for a symbiotic relationship, adaptive morphological and physiological approaches for enhancing P acquisition have developed by plants to combat restrictions of the rate of symbiosis in P-constrained states. These approaches are harmonized at multiple levels and include upholding of high amount of P in nodules than the surrounding tissues/organs; enhancement of root surface area, amount of root exudates excretion, and articulation of transporters and aquaporins for improved uptake of P; increase in fixed N per unit of nodule in order to reimburse decrease in nodule number; etc. (Vance 2001; Vance et al. 2003; Schulze 2004; Verma et al. 2015b). The enhanced P acquisition actively involved in enhancing the efficiency of BNF in nodules which largely contributes to N balance in the soil. Nearly all legume cultivars grown by the farmers exhibit all these approaches, thereby presenting a superlative way to maintain soil health with the aim of sustainable agriculture by improving N and P availability in soil. Therefore, legumes have a vital function ineffectual management of dependence on inorganic fertilizers and improving soil fertility.

6.2.4 Recovery of Acid Soils

Intensive agricultural system has resulted in reduced soil pH especially in humid regions, making the soil more acidic which is a solemn way to degrade agricultural terrain (Behera and Shukla 2015). The continuous application of a large amount of ammonium-based N fertilizers to the soil ecosystems, surface leaching of NO3- ions, acid rains, and harvesting of alkaline plant materials from the arable lands are the major factors rinsible for soil acidification. In turn, this acidified soil is a major obstruction for crop productivity in several provinces across the global cultivated areas (Baquy et al. 2017). Von Uexkull and Mutert (1995) examined that nearly 30% of the entire landscape of the world and about 50% of promising arable terrains are acidified. This vast territory is required to accomplish enormous food productivity in order to combat food challenges. Additionally, the intensive agricultural practices and foliage clearances to obtain an immense amount of energy further intensify the mortification processes, thereby decreasing soil fruitfulness (Wu and Tiessen 2002; Meena et al. 2015b).

Legume farming assisted with liming and cautious P supply is a primary step for recovery of acidic soils under stumpy N and P conditions (Von Uexkull and Mutert (1995). Legume farming adds considerable amounts of residues to the soil ecosystem which over time increase the soil organic matter, thereby helping in combating problems related to the acidity of the soil. Furthermore, the development of such legume cultivars which are able to grow under acidic conditions with low P and N availability has been an astonishing achievement. The preparation of soybean (Glycine max L. Mer.) germplasms and rhizobial cultures able to withstand in acid soils of Brazilian Cerrado allowed Brazil to turn into a primary exporter of soybeans (Spehar 1995). It has been found that acid soils have recovered in Brazil owing to the use of fast-growing legume trees (FGLTs) and their corresponding symbiotic associates (Chaer et al. 2011) under constraints of soil acidity. Therefore, the addition of legumes in intensive agricultural system prevents runoff of the frail soil surface, thereby helping in reinstating soil organic content and richness.

6.2.5 Carbon Sequestration

The agricultural production processes also release a significant percentage of greenhouse gases which further add to global warming. The various processes behind the emission of greenhouse gases can be summed up as the processes relating to the production and application of the fertilizers, use of machinery, agronomic practices, and several soil processes also characterize the primary mechanisms toward the emission of such gases to the atmosphere from the cultivated areas (Gan et al. 2012; Dhakal et al. 2016). At the same time, agricultural practices are also responsible for the mitigation of various greenhouse gases. In this line, the inclusion of legumes in the cropping system provides numerous benefits including decreased dependence on nitrogenous fertilizers along with the mitigation of carbon footprints (Plaza-Bonilla et al. 2018; Meena et al. 2018b).

Soil carbon (C) sequestration refers to the process of conveying of atmospheric CO2 into the soil of a particular place via its plants. There are a number of benefits of soil carbon sequestration comprising enhanced biodiversity, progressing nutritional security, growing renewability, and water quality, along with the strengthened nutrient recycling (Lal et al. 2015; Meena et al. 2017a). In agricultural systems, the rates of soil carbon sequestration strongly differ with the growth of diverse categories of crops (Zhang et al. 2010). In this regard, the crop residues of leguminous plants are supposed to be more likely to stabilize soil carbon (Drinkwater et al. 1998). The soils which have been deteriorated due to physical degradation, structural decline, and/or having reduced biodiversity can be restored by cultivating legume crops which are considered as the effective agents for improving soil organic carbon. The soil C sequestration is more pronounced in leguminous plants as compared to other nonlegume crops due to their leaf-shedding ability along with the ability of superior biomass production below the ground, and this effect is more pronounced if the farming practices of legumes are further accomplished in mixed farming along with the practice of crop rotation (Kumar et al. 2018a, b). The carbon storage is further reported to be higher when the agronomic practices of legume cultivation are further accompanied by the other management practices such as no-tillage and mixed cropping (Veloso et al. 2018).

Furthermore, legumes also affect the soil biology, and thereby they potentially enhance the development as well as maintenance of the soil aggregates which further enhance the soil carbon storage by protecting it from decomposition. So, the net effect of leguminous crops on the SOC and the other structural attributes of the soil depend upon the interactions between the soil components and the crop residues (Oliveira et al. 2019; Varma et al. 2017b).

Under the practices of no-tillage, the legume plants store the soil carbon either through the symbiotically fixed nitrogen which further increases the grain and the plant biomass or through the inputs of biomass associated with various plant parts (Amado et al. 2006). There is a significant increase in the C and N content of the soil when legumes are introduced in the grassland ecosystems, and thus it also influences the community productivity and there is a significant increase in the amount of soil C when legumes are cultivated with grasses in a definite proportion (Li et al.

2016). Leguminous plants are also found to reduce carbon footprints by controlling emission of greenhouse gases when grown in rotation with rice which is considered as "high input-high loss-high pollution" agricultural system (Cai et al. 2018; Meena and Lal 2018). Under the temperate climatic conditions, the insertion of grain legumes in the conventional cropping must go together with the parallel annexation of cover crops with the intention of attaining an advantage from the grain legumes (Plaza-Bonilla et al. 2016; Kumar et al. 2017a).

6.3 Effects on Soil Properties

Intensive agricultural practices lead to the degradation of soil aggregates resulting in soil erosion and loss of SOM (Garcia-Orenes et al. 2009; Meena et al. 2015e). Consequently, other physicochemical and biological properties of soil get adversely affected and result in making the soil infertile and decreasing crop productivity to a great extent. Legumes as cover crops increase SOM which aids the soil particles to aggregate, and the mulching of crop residues obtained from leguminous plants is considered a good technique of sustainable soil management as it precludes the erosion of soil, improves water retention capability, helps in refurbishment of soil biodiversity, buffers temperature fluctuations (Chen et al. 2018), and thus helps in the improvement of the soil structure (Fig. 6.2).

6.3.1 Physical Properties

The properties of soil are a matter of grave concern because of their steady degradation as a consequence of intensive agricultural system (Dexter 2004). In soil physical properties, the underprivileged water percolation and infiltration, dispersion of aggregated soil particles due to extensive tillage practices or wind/water runoff, less water retention capability, decreased pore size, deprived aeration, etc. are major

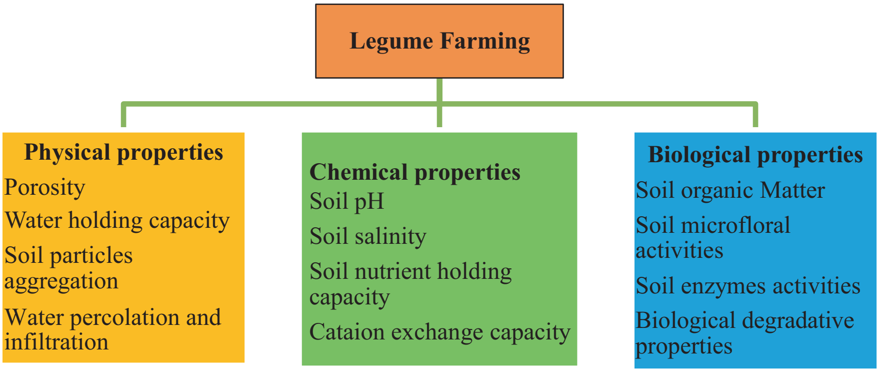

Fig. 6.2 Soil properties influenced by inclusion of legumes under intensive agriculture system

characteristics of poor quality of the soil. These physical soil properties are manipulated either naturally or by several mankind operations. Crop productivity gets negatively affected by these low-grade properties of soil.

Soil quality is generally considered as a reflection of crop yield. However, a number of researchers remarked that qualities of soil do not have a solitary determinant and numerous observations of a variety of physical assets needed to amalgamate. For instance, the term "agrophysical index" refers to the norm of ten different physical properties of soil (Dexter and Czyz 2000). The productive soil is usually characterized by its aiding effects on plant growth and development, their water retention capability, adequate availability and supply of plant nutrients, SOM reserves, active biological properties, and ample supply of aeration (Burger and Kelting 1999). The governance of all these characteristics is a major contribution of soil physical properties.

Legumes, as cover crops, act as a conditioner for soil since these positively affect the microflora populations in soil by providing substrates to them, thereby increasing degradation of residual plant litters and addition of OM to the soil in a huge amount (Lal 2011; Yadav et al. 2017c) which results in prevention of soil erosion by wind/water, enhancement in aggregation of soil particles and water holding capacity, etc. Therefore, legumes play a very significant role in the revitalization of soil and offer an advantageous strategy to improve soil health for sustainable agriculture.

6.3.2 Chemical Properties

The intensive agricultural practices have momentous adverse effects on soil chemical properties such as soil pH, salinity, nutrient holding capacity, cation exchange capacity, etc. which essentially contribute toward maintaining the physical as well as biological aspects of soil and thus improving soil quality. The frequent and colossal application of inorganic fertilizers to achieve high productivity leads to the deterioration of the uppermost fertile layer as well as the deeper soil by altering physicochemical properties, and as a result, crop productivity decreases. Legume farming has tremendous positive effects on soil chemical properties. Especially, soil pH is decreased by the production of organic acids and CO^2 upon degradation of soil OM added of legumes, and concomitantly, pH is raised also due to the reduction of H+ into H2O and CO_2 (Buragohain et al. 2017; Meena et al. 2018a; Mitran et al. 2018). Therefore, legume farming acts like a buffering agent for the soil by maintaining its pH. Furthermore, legume farming helps in the drainage of nutrients from deeper layers of soil by means of their specific root system and detained within the plant. The nutrients of residual plant litters undergo through recycling processes by residential soil microflora and aid in augmentation of SOM. The SOM acts as a slow-liberation reservoir of N supply which can complement N requirement for crop production, thereby reducing the need for inorganic fertilizers and consequently N losses (Becker et al. 1994). Addition of legume farming in intensive agricultural system reduces soil and water pollution to a very large extent. Legume farming also helps in increasing the growth of P-solubilizing/mobilizing microorganisms and plays a very significant role in P acquisition and reduction of external P supplements. Therefore, incorporation of legumes in current agricultural system buffers the soil pH which improves nutrient holding capacity as well as cation exchange capacity of soil and acts as a key driver for sustainable use of soil to ensure food availability.

6.3.3 Biological Properties

The abundance, as well as diversity of microorganisms, is directly proportional to the plant production comprising the above- and belowground biomass. The presence and abundance of microbial life are directly involved in the nutrient accessibility along with the transmission of nutrients from the soil to plants, thus improving soil fertility and plant-soil health (Duchene et al. 2017; Meena et al. 2014). The practice of intercropping with legumes helps in the development of diverse kinds of roots and thus is responsible for changing complete root distribution as well as architecture, along with the modification in the process of exudation in the rhizosphere. Thus, it will strongly influence the microbial community along with their interactions with the plant, thereby promoting beneficial attractions. Intercropping of cereals with legumes also promotes complementarily and facilitation in the agroecosystems (Duchene et al. 2017). The chemical properties of the rhizospheric zone can be modified by legumes. The root systems of cereals and legumes are not separate and are highly amalgamated. Therefore, the modified microbial diversity of rhizosphere with particular bacteria is beneficial for legumes as well as cereals.

Legumes are also supposed to promote the colonization of arbuscular mycorrhiza (AM) in agroecosystems receiving low inputs as legumes are actively engaged in tripartite symbiotic relationships (Rhizobium-legume-Mycorrhiza) (Pivato et al. 2007). There is a gradual enhancement in the diversity and abundance of the mycorrhiza under legume cultivation. There is secretion of some compounds called flavonoids which act as the promoters for the establishment of AM. The AM symbiosis also has strong effects on the organization and functioning of neighboring bacterial populations (Marschner and Timonen 2005).

6.4 Biocontrol

Legumes are considered as a potential agent to meet the massive food demands and adequate food availability for briskly growing global human population. The harmonized cereal food production with legumes represents a premium source of food quality enriched with protein contents. Nevertheless, cereal, as well as legume grains production, is sternly affected by quite a lot of pressures including an attack by different pests, pathogens, nematodes, and weeds which are responsible for severe decline in crop yield and quality as well (Mishra et al. 2018; Meena et al. 2017c). Usually, synthetic pesticides and weedicides are used to suppress/kill the pests, pathogens, and weeds. These chemicals are generally nonbiodegradable and persist in the soil for many years leading to severe health perils to human beings, vegetations, as well as animals and environmental ventures.

These consequences have headed for increased transferal of researcher's consideration in the direction of more secure and reliable technologies for managing the biotic stresses. In recent times, suppression/killing of pests, pathogen, and weeds using microbes as biological control agents (BCAs) has presented a commanding substitute to these hazardous chemicals aiming sustainable agriculture (Solans et al. 2016; Verma et al. 2015a).

6.4.1 Disease and Pest Control

In crop production, the average loss owing to diseases caused by pathogens and pests attack per annum has been anticipated to be about 17.5% of total losses in India (Dhaliwal et al. 2010). In diseases and pests favoring environments, up to 100% damage has been accounted for to a variety of legumes in Asia and Africa (Mishra et al. 2018). For instance, spotted pod borer (*Maruca vitrata*) in pigeon pea (Margam et al. 2011) and pod borer (*Helicoverpa armigera*) in pigeon pea (Rani et al. 2018a, b) and chickpea production (Ahmed and Awan 2013) stay the most imperative pests accounting for substantial losses responsible for immense economic mutilation.

Therefore, diseases and pests control present intermittent challenges to the farmers whose management is very crucial for managing the economy of a country, and these challenges may be greater for the coming generations due to increased resistance of pests and pathogens against pesticides in varying climatic conditions. Nonetheless, a range of impediments by means of antagonism, predation, competition, parasitism, etc. from other microbial species have a vital role in pest management practices. Furthermore, intensification of these impediments robustly affects the feasibility of agricultural pests and appears as sturdy strategies for prevention of falling agricultural productivity (Lin 2011). Legume farming has been accounted for the proliferation of microfloral population in soil by providing substrates for their growth and development which aids in the reduction of occurrence of pests and phytopathogens (Bybee-Finley et al. 2016). Additionally, IPMPs including the establishment of improved crop varieties, crop rotations, and intercropping with legumes symbolizing amalgamated soil richness and pest supervision strategies also present vital approaches for reducing economic losses and affirm agricultural sustainability along with food certainty.

6.4.2 Weed Control

The success agricultural field is largely meant for weed interference. Continuous cropping handled to the evolution of a number of autotrophic weeds which have well adapted and occupied various niches left available in the agroecosystems. In addition, there are other types of weeds known as parasitic weeds that have acquired the crops mainly as their source of food resource which enable their survival in a large number at even the nutrient-poor sites (Sauerborn et al. 2007). The parasitic plants have gained severe economic importance as they greatly reduce the yield of the crop along with its quality. There is the removal of minerals, photosynthates, and water from the crop field by these weed species, and these losses greatly reduce the ability of the host to nurture and compete (Dorr 1997). Whenever a plant is grown in the vicinity of the other plant, their interactions lead to the alteration of the immediate environment which further affects their procurement of these resources. The changes produced may either be qualitative or be quantitative. The quantitative changes can be well defined by water and nutrient depletion and reduction in the intensity of light by shading, but the overall result of both the types of changes is an alteration in the production (McDonald and Gill 2009). The competition between weed and crop is often dominantly pronounced when a dominant weed falls in the same season of the crop production even though the management practices can strongly influence the weed burden in a field. Although use of herbicides is an effective way of controlling weeds, the ill effects of herbicides and increasing environmental concerns have directed toward the use of an effective alternate measure to control weeds.

Thus, responding to such challenges, the concept of integrated weed management has been largely promoted. The most important concept of this approach is the introduction of competitive cultivars (Lemerle et al. 2001; Meena et al. 2018a). The growing competitive cultivars provide numerous benefits relating to the reduction in the growth and prolificacy of the weeds (Williams et al. 2008). The practice of using living mulches which is defined as “a cover crop is sown either before or with the main crop and maintained as a living ground cover throughout the growing season” (Hartwig and Ammon 2002) also appears to be an important solution. This practice can provide a total weed control or reduces the number of chemicals used to suppress/kill the weeds (Lorin et al. 2015). In a study by Cadoux et al. (2015), positive results for weed control were observed when the living mulch of legumes was used, and its effect was assessed in terms of ground covered by weeds in a few sites and for three legume mixtures.

Legume crops can make potentially outstanding living mulches, thereby increasing the competitiveness of the whole intercrop against the weed plants (Naudin et al. 2011). Lorin et al. (2015) also tested the efficacy of different leguminous plants for controlling the weeds and observed a positive result with a reduction range of 20–75% in the absence of chemical herbicides. The practice of introducing living mulches of legumes didn’t completely preclude weed growth but was also noticeably a pertinent agroecological solution for declining herbicides, while growing the sustainability and variety of weed-control tactics in cropping systems.

6.5 Legumes as Green Manure

At the moment, various countries have entered into the post-green revolution stage due to the extensive applications of synthetic chemicals in intensive agricultural system and are a stand in front of a very giant problem of decreasing crop yields (Meena and Majumdar 2016; Sihag et al. 2015). The soil health management practices at an ample scale in order to maintain soil productiveness represent a crucial aspect for increasing crop yields and becoming a matter of grave concern for farmers and scientists. The application of macrobiotic mucks, counting green manures, symbolizes effective approach to enhance soil fruitfulness in many aspects (Fageria 2007).

Green manure refers to the inclusion of crumbled fresh/parch plant residues into the soil which undergoes biodegradation with the help of soil residential microflora and contributes to SOM. Legumes are the efficient green manuring crops as their decomposed plant materials after harvest can improve nutrient-binding and water-holding capacities of soil, reduce soil erosion, and increase SOM and thereby improve different soil properties aiding intensified crop productivity (Dinnes et al. 2002; Fageria and Baligar 2005; Meena et al. 2017b). Legume green manuring can be classified into two categories depending upon the site of manuring, i.e., in situ green manuring and ex situ green manuring. In case of in situ green manuring, legumes are cultivated and added in the soil at the same site, while in case of ex situ green manuring, residual legume trashes are gathered from proximal sites and added to the soil before the sowing of next crop. Moreover, legumes have a number of attributes such as BNF, concise period, resistant to abiotic as well as biotic stresses, environmental flexibility, rapid production, simplicity in addition to soil, etc., thereby enabling improved supervision of agricultural sustainability (Meena et al. 2018b; Sofi et al. 2018).

6.6 Diversification

Intensified agriculture has increased automation of the agricultural practices and extensive use of agrochemical aiming to meet enormous food demands. Since the 1990s, this agricultural system is under the challenge of substituting it with organic, sustainable, and eco-friendly farming ensuring food availability for future generations.

The well-managed agricultural practices have great potential to enhance biodiversity and ecological sustainability (Tscharntke et al. 2005). A very close alliance with crop cultivators is necessary for the continuance of diversification and ecological functions. Legumes play a very significant role as diversifying crops since legumes are able to increase SOM which makes them able to aid the development of microbial populations capable of breaching the succession of pests and pathogens. Legume farming also increases the population of beneficial microflora in soil helping in degradation of OM and nutrient recycling (Voisin et al. 2013; Ram and Meena 2014). Increased amounts of nutrients facilitate to enhance the diversity of other beneficial resident microbes and crop productivity and minimize input requirements for other crops grown in alternation to the legumes. These applications of legume farming improve the quality of crop terrains enhancing crop diversity as well and make them appropriate candidates to include in low-input sustainable agriculture practices. Therefore, legumes are a substantial part of ecological progression in the direction of a sustainable agriculture system.

6.7 Conclusion and Future Prospective

The practice of modern agriculture produces high yields but also generates a trenchant amount of ill effects by substantial consumption of chemical inputs and conventional sources of energy, thus is presently arising question on this practice. The contemporary past has clearly exposed its humongous costs and its effects on the public as well as environmental health along with its effects on soil health. The current research emphasizes the significance of planning cropping systems using ecological principles and ecosystem amenities for the enhancement of agroecosystem sustainability and product efficacy, divesting the chemical usage and employment of nonrenewable energy resources. Legumes being actively involved in nitrogen dynamics and various other attributes of environmental sustainability are therefore considered as an important tool in soil health improvement. Furthermore, grain legumes play a very significant role in maintaining good health of the soil and its fruitfulness along with their nutritional viewpoint. However, swarm fissures of awareness associated with benefits of legume farming and their lasting optimistic influences on soil properties of different kinds of soils and soil functions are required to be filled, and perception of integrated management practices is needed to be explored. Consequently, it is utmost important to figure out the future needs and significance of legumes in maintaining sustainability and food availability.

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7 Legume Root Rot Control Through Soil Management for Sustainable Agriculture

Bita Naseri

Contents

Abstract

One of the most desired goals in sustainable agriculture is to wisely organize crop management programs which not only improve productivity but also do not disturb agroecosystem. To achieve this outstanding aim, there is no doubt that soil management methods should be considered as a fundamental part of optimizing organic agronomy. Legumes, which are long known as the important source of plant protein, have been recognized to be potential contributors to the sustainability of worldwide agriculture. However, proper cultivation of these

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valuable food crops is profoundly dependent on plant protection and production strategies. This chapter reviews the literature to provide an improved insight into an array of influential soil attributes and those soil-associated agronomic practices on legume root rot pathosystems for environment-friendly production perspectives. Root rot pathogens can strictly limit benefits of legume cultivation for farming systems via rotted roots, reduced root system expansion, and lower rhizobial nodulation. Legume root rots also cause further losses to crop productivity that discourage farmers from including them in their rotation programs. Therefore, it is crucial to control legume root rots by developing efficient agronomic practices to improve soil suppressiveness against pathogens according to sustainable agriculture and organic farming principles. Such efforts could allow us to not only enhance productivity and sustainability in legume cultivation but also optimize soil health and fertility for non-legume cultivation. Moreover, this sustainable way of suppressing pathogens based on efficient soil management methods can minimize production expenses due to synthetic fertilizers, fungicides, or herbicides.

Keywords

Agroecosystem · Fungi · Pathogen · Root rot · Soilborne · Suppressive soil · Sustainable agriculture

Abbreviations

C	Carbon
CO_2	Carbon dioxide
Fe	Iron
K	Potassium
N	Nitrogen
N_2-fixing	Nitrogen-fixing activity
N_2O	Nitrous oxide
NH_3	Ammonia
P	Phosphorous
SOC	Soil organic carbon
SOM	Soil organic matter
Zn	Zinc

7.1 Introduction

Legumes are valuable crops due to their direct and indirect benefits such as food, animal feed, green manure, rotational crop, soil health, and fertility. Under increasing pressure of food demand on agriculture, the widely proved benefits of legume crops for agroecosystems are more desired than ever. The noticeable role of root-nodule bacteria in improving crop productivity for legumes and non-legume crops has been much reported previously. As another advantage of legume cultivation, intercropping of cereal grains with legumes can improve acquisition of nitrogen (N), phosphorus (P), iron (Fe), and zinc (Zn) from soil; enhance grain production; suppress diseases, pests, and weeds; and increase plant biodiversity (Bedoussac et al. 2015; Brooker et al. 2015; Xue et al. 2016; Meena et al. 2015d). Because of symbiotic relationship of rhizobial bacteria with legumes, these valuable crops are less reliant on chemical fertilizers compared to non-legume crops. It has been documented previously that these beneficial soil microbiotas can fix 50–300 kg N ha^{-1} (Chen 2006; Sofi et al. 2018). These benefits of legume crops for agroecosystems have been entirely ignored in modern agriculture which seeks higher but non-sustained profitability through intensive fertilization of soils with chemicals. Furthermore, a majority of synthetic fertilizers become sorbed and bound to nutrient pools in field soil. For instance, a major part of P-fertilizers applied to pasture soils in Australia was absorbed by soil inorganic and organic P pools, so that only 35% of the fertilizer P was taken up by clover crops (McLaren et al. 2015; Kumar et al. 2018). However, another group of beneficial bacteria can dissolve bound forms of P in the soil and make it available to plants; thus, 30–50 kg ha^{-1} P-fertilization can be saved (Chen 2006). Therefore, advantages of growing legumes for sustain profits deserve much further consideration in future agriculture.

Attracting further attention of legume producers and users depends on minimizing threats in cropping systems. One of the most important crop damages in legume production is attributed to root rot pathogens which not only reduce productivity but also restrict bacterial symbiosis in root systems. Obviously, the control of these soilborne fungi seems difficult because of highly complicated chemical, physical, and biological properties in the soil environment. However, there are a number of promising agronomic and soil management methods in order to increase soil suppressiveness against legume root rots and decrease their detrimental effects on crop production. This chapter aims to remind us of the advantageous control of root rot diseases using sustainable and organic agricultural and soil management methods in order to benefit from legume cultivation as much as possible.

7.2 Crop Rotation and Residue Management

Soil-associated management practices involving rotation and residue management are proved to influence soil microbial activities and populations, nutrient availability, and root penetration resistance. These soil attributes have been illustrated by the model system of legume root rots. Productivity in rotated crops is typically 5–15% greater than in monoculture even with intensive fertilization or excluding symbiotic legumes from the rotation program (Liebman and Ohno 1998). Moreover, developing disease-suppressive soils by applying effective crop rotations appears to restrict soilborne diseases (Bailey and Lazarovits 2003; Yadav et al. 2017c). The suppressiveness which is mainly related to the soil microbiota occurs with increasing populations of actinomycetes and bacteria (Postma et al. 2008). When root rot diseases are not suppressed by naturally occurring antagonists, it is so wise to enhance soil suppressiveness by involving proper crops in rotation. Ancient Greek and Roman farmers used to rotate wheat (*Triticum aestivum* L.) with beans (*Phaseolus* spp.) or legumes, followed by either a green manure or a fallow period (Karlen et al. 1994). Over the years, a number of studies have evaluated the impact of rotational crops on legume root rots worldwide. In Australia, Sweetingham (1990) recommended cereals as the preferred break crop in lupin (*Lupinus angustifolius* L.) cultivation due to their improved yield and broadleaf weed control. In New York, Maloy and Burkholder (1959) reported that growing beans after wheat decreased bean root rot and improved yield. It is previously known that impacts of crop rotations on soil biota are also attributed to biological breaks with no host plants being grown (Altieri 1999). A minimum of 3-year rotation of bean with either wheat (Maloy and Burkholder 1959), oat (*Avena* sp.; Natti 1965), or other crops (Naseri and Ansari Hamadani 2014) reduced root rots and improved the crop productivity. According to earlier reports, planted beans after maize (*Zea mays* L.), wheat, barley (*Hordeum vulgare* L.; Abawi and Pastor Corrales 1990), and alfalfa (*Medicago sativa* L.; Román-Avilés et al. 2003) restricted bean root rots and improved production. In the greenhouse, gramineous plants such as maize and wheat were grouped as non-host of *Fusarium oxysporum* and *F. solani* of bean (*Phaseolus vulgaris* L.), respectively (Dhingra and Coelho Netto 2001; Khodagholi et al. 2013). Although Fusarium root rot developed on alfalfa, this legume had the lowest disease level among the legumes examined by Khodagholi et al. (2013). Naseri and Marefat (2011) examined 122 commercial fields for soil and agronomic characteristics, root rots, and yield and found that growing bean following maize reduced Fusarium root rot epidemics by 48% and improved bean productivity by 37%.

Considering the impacts of crop rotations on survival and saprophytic ability of pathogens in the soil (Wale 2004), *Rhizoctonia solani* populations decreased in soils of wheat, oats, barley, or maize fields but survived under cultivation of bean, pea (*Pisum sativum* L.), or potato (*Solanum tuberosum* L.) crops (Abawi and Widmer 2000). Furthermore, Manning and Crossan (1969) evidenced the inhibition of bean Rhizoctonia root rot using the maize debris even about a year after amending the stubble to the pot or field soil. It is previously documented that preceding crops can influence soil organisms through their organic inputs to the soil. With this regard, sustainable farming systems, which enhance soil inputs of carbon (C) and N via involving fibrous rooted crops and/or legumes in crop sequences, often increase populations and activities of soil microorganisms to a greater extent compared to conventional systems using chemical fertilizers (Altieri 1999). This is possibly why potato-bean rotations reduced charcoal and Rhizoctonia root rots compared to rotations of bean with alfalfa, bean, or maize (Naseri 2013c, 2014b; Naseri and Ansari Hamadani 2014). Moreover, cropping sequence (Kuo et al. 1997), duration, and timings of ‘fallowing’ (Halvorson et al. 2002) can influence the soil organic carbon (SOC) stocks and subsequently soil fertility. Growing pea after cruciferous (Muehlchen et al. 1990) and oat green manure (Fritz et al. 1995) can restrict root rot epidemics. Decomposition of crucifer residue and then degradation of glucosinolates release fungistatic sulphur-involved complexes within the soil system (Hossain et al. 2012). Decomposition of oat debris in soil releases fungistatic avenacin and saponins compounds which inhibit the growth of root rot pathogens (Deacon and Mitchell 1985; Williams-Woodward et al. 1997). It should be noticed that N fertilizations can nullify beneficial effects of carbonaceous debris of cereals and thus reduce SOC in the field (Majumder et al. 2008; Ashoka et al. 2017). Thus, chemical fertilization appears to minimize benefits outcoming from proper crop rotations that should be substituted or reconsidered carefully in future optimizations of sustainable legume cropping systems.

Although Fusarium wilt epidemics and soil populations of *F. oxysporum* and *Macrophomina phaseolina* in commercial bean cropping systems corresponded with previous crop, they had different correspondences with the type of preceding crop (Naseri and Hamadani 2017; Naseri and Tabande 2017; Meena and Meena 2017). El-Garhy (2000) evidenced that Rhizoctonia root rot of lentil (*Lens esculenta*) increased when cultivated after cotton and soybean and decreased after rice and maize, whereas Sclerotinia root rot of lentil increased after soybean (*Glycine max* L.) and maize and decreased after rice (*Oryza sativa* L.) and cotton (*Gossypium* sp.) cultivation. Abdel-Monaim and Abo-Elyousr (2012) evidenced larger populations of *F. solani* and *R. solani* in lentils grown after soybean, while cowpea (*Vigna unguiculata* L.) and sorghum (*Sorghum* sp.) as preceding crops reduced the populations of *R. solani* and *F. solani*, respectively. In addition, lentil grown after cowpea produced the highest seed yield, while soybean-lentil rotation had lowest seed production. In contrast to soybean, root exudates of cowpea and sorghum decreased mycelial dry weight of these two root rot pathogens in vitro (Abdel-Monaim and Abo-Elyousr 2012). These evidences suggest that microbial communities and activities in soil are greatly influenced by crop species used in rotation sequences. Abdel-Monaim and Abo-Elyousr (2012) proposed that root exudates of previous crops may impact on the growth of fungal pathogens in the soil and consequently on legume root rots. In addition to soil microbiota, according to previous documents, inclusion of specific crops in rotations can improve the competitive ability of the cultivated crops against weeds. For instance, rotations with allelopathic plant species may reduce weeds' growth. Sorghum, sunflower (*Helianthus annuus* L.), hemp (*Cannabis sativa* L.), and kenaf (*Hibiscus cannabinus* L.) are a number of examples for allelopathic crops which could act like herbicides by producing phytotoxic compounds (Batish et al. 2002).

7.3 Fertilization

A good farming practice can reduce carbon dioxide (CO_2) evolution from soil into the air and improve soil fertility and thus crop production (Lal 2004). Majumder et al. (2008) evidenced reductions in SOC due to chemical fertilization. Also, the significant role of inorganic fertilizers in environmental pollution cannot be ignored. Among the synthetic fertilizers, N-fertilizer raises denitrification and nitrous oxide (N_2O) emission to the atmosphere which are involved in global warming (Smith et al. 2008; Varma et al. 2017). Considering N-fertilizers also responsible for SOC emissions in the long run (Khan et al. 2007; Mitran et al. 2018), biofertilizers involving various microorganisms can prevent this shortcoming of inorganic N fertilization (Jeyabal and Kupuswamy 2001). Furthermore, it has also been documented that use of biofertilizers improves crop productivity and decreases environmental pollution (Mia and Shamsuddin 2010). Thus, much attention has been recently focused on the organic agricultural production worldwide by applying biofertilizers in order to avoid plant and environmental pollution and subsequently human health hazards (Sayed et al. 2015; Buragohain et al. 2017). As a result of detrimental impacts of N-fertilizers on agrosystems, it should be noticed that N-fertilizers can minimize beneficial impacts of carbonaceous residue of cereals on soil health (Huber 1963). Moreover, over-fertilization can enhance plant susceptibility to pathogens through increases in prolific growth of plant parts (Davies et al. 1997). These disadvantages of chemical fertilizers are particularly more detrimental to soils which have inherently low SOC contents (Mandal et al. 2007). In Iran, applications of 50–500 kg ha^{-1} urea (ammoniacal-N-fertilizer or NH_4-containing fertilizer) in 66.4% of the commercial bean fields at relatively low to moderate soil organic matter (SOM) levels (0.4–1.8%) intensified charcoal, *Fusarium* (early season; Naseri and Marefat 2011), and *Rhizoctonia* (at pod maturity; Naseri 2013a) root rots, and *Fusarium* wilt (Naseri and Tabande 2017) epidemics occurred across a diverse range of soil types and minerals in comparison with organic fertilization, manure application. Urea overuse was also related to larger *M. phaseolina* and *F. oxysporum* communities, and total populations of root rot pathogens in bean-farm soils (Naseri and Hamadani 2017). Similarly, greater soil NH_4-N contents corresponded with larger populations of *R. solani* and more severe bean *Rhizoctonia* root rots (Kataria and Grover 1987). Jones and Woltz (1975) also reported that more severe *Fusarium* wilt epidemics developed in cucumbers (*Cucumis sativus* L.) and watermelons (*Citrullus lanatus* Thunb.) due to urea fertilization at field-plot scale. It appears that soil type and mineral compounds can control the plant accessibility to fertilizers. For example, a considerable part of NH_4 supplied by urea fertilization is to be bound in clay minerals (Nieder et al. 2011; Meena et al. 2016). Unlike the nitrate form, the ammonium form of N-fertilizers intensifies bean-FRR epidemics (Abawi and Pastor Corrales 1990). The significant association of *Fusarium* root rot with the form of N-fertilizer has been reported previously (Ghorbani et al. 2008). This may explain why the overuse of urea as an ammonium form of N-fertilizers by majority of bean farmers in Zanjan intensified epidemics of *Fusarium* root rot in commercial bean crops (Naseri and Marefat 2011; Meena and Lal 2018).

In addition to high costs and environmental concerns, about 75–90% of the commercially produced P-fertilizers applied to soil are estimated to be bounded into complexes with certain soil elements (Zaidi et al. 2009; Dadhich and Meena 2014). Therefore, it is needed to identify an environment-friendly and economically alternative fertilization strategy that could provide sufficient P to crops. In this context, biofertilizers, especially phosphate-solubilizing bacteria, have attracted experts' attention worldwide. Populations of two fluorescent Pseudomonads with significant impacts on wheat growth, yield, and nutrient use reduced with increasing rate of

NPK fertilizers from 0% to 100% (Shaharoona et al. 2008). This group of beneficial bacteria also acted as biocontrol agents in pea crops (Negi et al. 2005). El-Gizawy and Mehasen (2009) reported that co-application of phosphate-solubilizing bacteria with synthetic P-fertilizers had notably improved seed production and the level of N, P, and Zn in bean seeds. Although applications of P-fertilizer corresponded with smaller total soil populations of bean root rot pathogens, in particular *F. oxysporum*, *F. solani*, and *M. phaseolina* (Naseri and Hamadani 2017), finding an appropriate alternate fertilizer seems necessary because of synthetic P-fertilizer shortcomings.

Therefore, because of increasing expenses, potential environmental pollution, and soil health deterioration as results of using chemical fertilizers, there is an urgent need to adopt effective organic fertilizers for sustainable agriculture. Furthermore, continuous fertilization with chemicals had deleterious impacts on soil productivity. In addition to biofertilizers, the application of composts has attracted much attention as one of major alternatives to chemicals for fertilizing soils and controlling soilborne pathogens in sustainable agriculture. Composts have long been used in agriculture as an amendment for managing soil physical properties, SOM, and fertility (Brady and Weil 2000; Hoitink et al. 2001; Stone et al., 2004; Meena et al. 2014). The suppressiveness of composts against plant pathogens has been mainly attributed to the presence of antagonistic agents and unknown chemical compounds in the compost, activation of antagonistic microorganisms in the rhizosphere, and induction of systemic resistance in plants (Hoitink et al. 2001; Datta et al. 2017). For instance, Zmora-Nahum et al. (2008) reported that alkaline pH and high ammonia (NH_3) concentration of municipal sewage sludge and yard waste compost corresponded with inhibition of germination of *Sclerotium rolfsii* sclerotia. Earlier findings demonstrated that the suppression of *Rhizoctonia* root rot is influenced by the type of compost applied to soil (Stone et al. 2004). Scheuerell and Mahaffee (2004) reported that the extracts of composted chicken manures suppressed diseases by more than 50% greater than the extracts of either vermicompost or dairy manure. For the bean-*Rhizoctonia* pathosystem studied at plot scale, Joshi et al. (2009) also found higher disease suppression in poultry manure and plant-based composts as compared to farmyard manure, vermicompost, and spent mushroom compost. They observed high levels of root rot suppression (>33%) and productivity in the poultry manure which also increased rhizospheric populations of *Trichoderma* spp. and fluorescent Pseudomonads. Soil antagonists like species of *Trichoderma* and *Pseudomonas* have been known as major determinants of compost suppressiveness against *Rhizoctonia* root rots (Hoitink et al. 2001; Krause et al. 2001). It has been suggested that the type of organic substrate determines the suppressiveness level of *Trichoderma* spp. in composts against *R. solani* (Tuitert et al. 1998).

Because applications of animal manures as fertilizers commonly improve the density and activity of soil biota, the highest microbial and protozoan activity occurs in organically fertilized farming soils (Altieri 1999). In fact, microbial biomass C, which is known as a soil C pool, has been used to estimate soil quality. Moreover, manuring can also affect the SOC stocks (Hartwig and Ammon 2002; Yadav et al. 2018b). In South Africa, Belay et al. (2001) evidenced that maize yield, total C, N, and available P levels, and microbial populations in the soil were increased by applications of manure (a mixture of cattle dung and compost). Documents have demonstrated that improvements in SOC are directly associated with the amounts of organic substrates incorporated into the soil. In the production of snap beans, the equal efficiency of low rates of broiler litter and chemical fertilizers has been evidenced (Brown et al. 1993). Riegel and Noe (2000) reported that applications of poultry litter can result in variations in soil populations of fungal and bacterial saprophytes or antagonists of plant pathogens. Osunlaja (1990) suggested that the old environment-friendly practice of manuring not only reuses agricultural wastes but also restricts the development of soilborne diseases. Therefore, an advanced understanding of animal manures in interaction with legume root rots is required for sustainable agriculture purposes. Antagonistic activities were suggested to be responsible for disease biocontrol, because gamma irradiation eliminated the suppressiveness of composted cattle manure against bean *Rhizoctonia* root rot (Gorodecki and Hadar 1990). Elsewhere, none of non-composted poultry litter amendments decreased snap bean *Fusarium* and *Rhizoctonia* root rots and soil populations of *R. solani* and *F. solani*, while these amendments resulted in larger soil populations of fungal saprophytes, which may act as the biocontrol agents of root rot pathogens (Sumner et al. 2002). In Iran, applications of animal manure by farmers reduced the development of *Fusarium* and *Rhizoctonia* root rot epidemics over the growing season and then enhanced bean production compared to chemical fertilization or the lack of fertilization (Naseri and Moradi 2015; Naseri et al. 2016; Meena et al. 2018c). These interesting findings obtained across greatly diverse agrosystems with widely different soil environments and microbiota evidenced benefits of SOM amendments in the form of manuring for bean production. Therefore, it is essential that future research would optimize amending soil with manures and composts for sustainable legume production (Fig. 7.1).

7.4 Plant Density

It is previously known that longer distances between host plants due to the reduced number of hosts per unit area can exert stressful conditions for airborne pathogens (Wolfe 2000; Fernández-Aparicio et al. 2010). However, concise mechanisms responsible for such plant density effects are difficult to identify for soilborne pathogens due to the highly complicated interrelationships between plant, soil, and microbiota. Silbernagel and Mills (1990) evidenced that the impact of plant density on yield was dependent on the cultivar-disease-resistance interaction for snap bean *Fusarium* root rot. They reported that narrow row spacing enhanced seed production in the disease-resistant cultivars, but not in susceptible cultivars. Naseri and Marefat (2011) indicated that the most severe epidemics of *Fusarium* and *Rhizoctonia* root rots occurred in the densest populations of bean plants (32–68 plant m^{-2}) which produced fewer pods and seeds per plant. They suggested that stress factors like limited access to light, nutrients, and water because of competition between overlapping roots and foliage and wet canopies as a common result of dense plantings must have intensified the development of bean root rots. Furthermore,

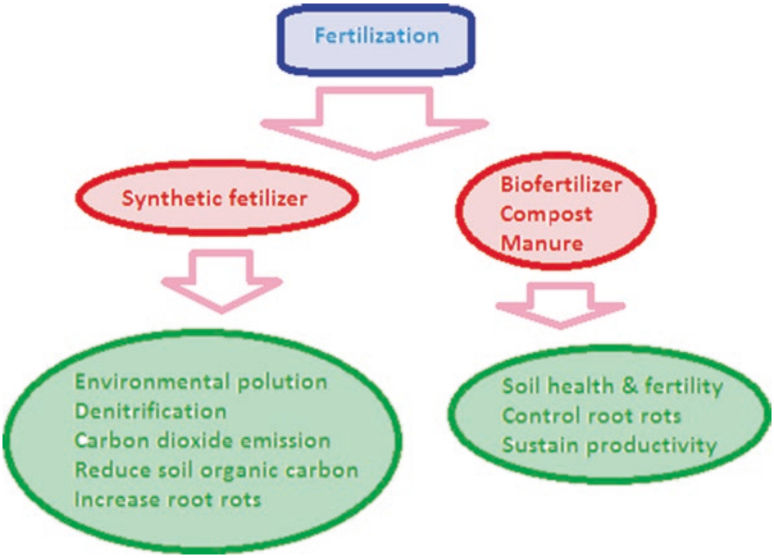

Fig. 7.1 Fertilization methods, soil environment, and legume root rots

it has been documented that dense plantings can transmit soilborne pathogens via overlapped roots to adjacent plants and increase the spatial distribution of root infections (Long and Cooke 1969). The extension and development of root systems within a soil describe the crop accessibility to water and nutrients (Ehrmann and Ritz 2014; Verma et al. 2015b). In contrast to *Fusarium* and *Rhizoctonia* root rots, the detection of lower levels of charcoal root rot in densely planted bean crops (Naseri and Taghadossi 2014) suggested that air wetness due to overlapped foliage and then excess soil moisture following irrigation has presumably reduced the disease spread across diverse agrosystems. Hot and dry conditions have been previously reported as favourable conditions to *Macrophomina* root rot epidemics (Abawi and Pastor Corrales 1990; Olaya et al. 1996).

On the other hand, improved crop competitiveness with weeds, decreased aphid and virus infestation, and increased plant height at harvest are supposed to enhance seed production in dense plantings of legumes. The secondary advantages of high sowing rates for faba bean (*Vicia faba* L.; Loss et al. 1998), lentil (Siddique et al. 1998), and chickpea (*Cicer arietinum* L.; Jettner et al. 1999) have been documented previously. Jettner et al. (1999) reported that the optimum plant density was 50 plants m^{-2} yielding about 1.0 t ha^{-1} for most chickpea crops in south-western Australia, while plant densities >70 plants m^{-2} can produce the highest yield levels (>1.5 t ha^{-1}) provided that root rots are absent. In lupins, the optimum planting density in most situations ranged from 40 to 45 plants m^{-2} (Sweetingham 1990). Because dense plantings can exacerbate fungal diseases, growing smaller plant populations is recommended for disease-prone regions. In intercrops of maize-bean and maize-sunflower, Fleck et al. (1984) suggested that dense cropping may have suppressive effects on weeds. In a comparison of four soybean seeding rates (24, 30, 36, and 42 seeds m^{-2}) in Iowa, seeding rate corresponded negatively with weed biomass and positively with productivity (Arce et al. 2009). Place et al. (2009) suggested that increasing seeding rate can be incorporated as an influential strategy for controlling weeds in organic production of soybeans. Furthermore, increasing the competition for soil N through dense planting of either faba beans or barley-faba bean intercrops substantially enhanced N-fixation in faba beans (Danso et al. 1987). Considering the positive outcomes of crop density on legume productivity, further research is warranted to determine whether the noticeable role of dense planting in developing root rot diseases, increasing disease pressure on agrosystems, and consequently reducing crop production could be managed with the help of other agronomic methods in order to benefit from dense cropping in sustainable legume cultivation.

7.5 Planting Date

According to earlier documents, legume root rots can be effectively managed by choice of proper planting date. It seems variations in root rot epidemics due to differences in sowing times could be attributed to variability in air temperature and rainfall which in turn can influence soil temperature and moisture. For instance, postponing chickpea sowing from mid-December to mid-March resulted in planting at lower soil-moisture levels and higher temperatures in southern Spain that favoured development of *Fusarium* wilt epidemics (Navas-Cortés et al. 1998). Likewise, differences in temperature were known responsible for variations in chickpea wilt in India and root rot epidemics in California (Westerlund Jr. et al. 1974; Gupta et al. 1987). In bean crops, the interaction of root rot intensity with planting date was also attributed to environmental conditions. In Iran, more severe epidemics of charcoal, *Fusarium*, and *Rhizoctonia* root rots developed in earlier planted bean crops under cold and wet climatic conditions in May (mid-spring in the study area, Zanjan province) compared with June (early summer, Naseri 2013c, 2014b, c; Naseri and Marefat 2011; Meena et al. 2018). This report is in agreement with an old document on the most severe *Fusarium* root rot epidemics developed in beans sown in cold and moist soils (Burke and Miller 1983).

An advanced understanding of the association of bean root rots with this important environmental parameter can assist in wise selection of appropriate sowing date in disease-prone regions (Naseri and Hemmati 2017; Layek et al. 2018). It is previously documented that bean seedlings grow more rapidly at relatively high temperatures, emerge from soil, and escape infection by soilborne pathogens (Bolkan et al. 1974). In Canada, early sowing of lentil commonly improves productivity; however, spring plantings into cold soils delay seed germination and possibly predispose seedlings to root rot diseases (Hwang et al. 2000). In white beans, more severe *Fusarium* root rot happened at 21 °C compared to 14 °C and 28 °C temperatures, while bean plants had better growth at soil temperatures of 28 °C than at 14 °C or 21 °C (Sippell and Hall 1982). This presumably explains why slowly growing beans in cold soils may be at greater risk of soilborne diseases due to longer pre-emergence stage. Abawi (1989) also recommended late planting of beans in the relatively warm soil (>21 °C) reduced *Rhizoctonia* root rot, which occurs more severely in cold and wet soils. Elsewhere, the most severe epidemics of *Rhizoctonia* root rot developed in the warm (>20 °C) and moist soil (Allen and Lenne 1997). van Bruggen et al. (1986) added that the development of *Rhizoctonia* root rot was dependent primarily on temperature (optimum at 24–30 °C) and secondarily on soil moisture. These different findings on the optimum soil temperature and wetness for the establishment of *Rhizoctonia* root rot may reflect variations in environmental, pathogenic, and host traits between various studies. In the controlled environment, *F. solani* f. sp. *phaseoli* did not grow at 5 °C, while it had growth at 15 °C, 25 °C, and 35 °C, with maximum growth occurring at 25 °C (Khodagholi et al. 2013). This optimum temperature agrees with the earlier report provided by Kausar et al. (2009). Although low soil moisture and high soil temperatures (28–35 °C) can intensify charcoal root rot epidemics (Abawi and Pastor Corrales 1990; Smith and Wyllie 1999), the greatest infection of bean plants by *M. phaseolina* was detected at temperatures of 15–20 °C and moistures of 15–25%, and then infections decreased with increasing soil temperature and moisture (Dhingra and Chagas 1981).

Early planting of lupins is always recommended for higher yield levels; however, it is crucial in the high root-rot-risk areas to optimize planting date so that seedlings can grow beyond the most susceptible 0- to 4-leaf stage prior to cool and moist climatic conditions (Sweetingham 1990). In Canada, early seeding of lentil in mid-May was needed for maximum yield at field-plot scale, and the maximum infection by *Fusarium avenaceum* was observed at warm temperatures (20–27.5 °C) in the controlled environment (Hwang et al. 2000). Despite reductions in root rot epidemics in highly diverse commercial farming systems (Naseri 2013c, 2014b, c; Naseri and Marefat 2011; Datta et al. 2017b), the lack of yield improvement may be partially attributed to coincidence of pod maturity and inappropriate cold weather of early autumn in lately planted bean crops. However, in experimental plot-scale studies (Naseri and Mousavi 2013), late planting decreased pod and seed production for deep plantings (10 and 15 cm) but enhanced productivity in shallow plantings (5 cm). In Iranian chickpeas, mid-autumn-seeded crops produced the highest yield and lowest *Fusarium* wilt compared to late-autumn- and late-winter-sown crops (Younesi 2014). Advancing planting date from late winter to late autumn reduced chickpea *Fusarium* wilt by 24–41% and improved yield by about twofold (Younesi 2014). Therefore, planting date as an influential agronomic practice with linkage to soil conditions should be incorporated into management programs developed for sustainable legume production.

7.6 Planting Depth

Considering interactions with soil moisture and microbiota, the depth of seeding appears to be influential in producing legumes especially from a sustainable agriculture perspective. For instance, deep sowing improved the crop growth and production of chickpeas and faba beans presumably due to greater root accessibility to soil water (Siddique and Loss 1999). In chickpea field, the soil water storage was significantly affected by soil depth (Barzegar et al. 2003). Singh et al. (2013) also reported that seeding at 7.5 cm depth improved seed production in faba beans. It has been documented that seeding depth also influences P and potassium (K) availability (El-Gizawy and Mehasen 2009). However, deep planting has been also known responsible for delay in plant emergence and predisposition of seedlings to *Fusarium* root rot pathogens (Abawi and Pastor Corrales 1990). Therefore, in addition to the interaction of planting depth with soil moisture and nutrients accessibility, this agronomic practice is also associated with soil biological status. Because of the highest concentration of spores of *Pleiochaeta setose* in the top 2 cm of soil, Pleiochaeta root rot is more severe in lupins planted as shallow as 2 cm (Sweetingham 1990). Hence, Sweetingham (1990) recommended farmers to plant lupins at a sowing depth of 5 cm to not only reduce predisposition of the root to a high concentration of pathogen spores but also precede the germination and growth of seed due to greater retention of soil moisture. Shallow sowing was similarly advised to lower bean infections as a result of shorter duration of predisposition to *R. solani* inoculum which is denser at shallower depths (Papavizas et al. 1975; Abawi 1989). For this reason, seeding at a depth of 1.5–2.5 cm has been recommended to restrict *Rhizoctonia* root rot in snapbeans (Leach and Garber 1970). For *M. phaseolina*, microsclerotia of *M. phaseolina* are commonly concentrated in the top 30 cm of field soils (Bruton and Reuveni 1985), with the densest populations being detected at a depth of 0–5 cm (Lodha et al. 1990). In a field study on bean crops, seeding at a shallow depth of 2.5 cm was identified as the most influential agronomic practice to restrict root rot development when compared to hilling depth and fungicide use (Brien et al. 1991), whereas deep sowing of bean was ineffective on *Rhizoctonia* root rot in the presence of the soil antagonist, *Trichoderma harzianum* (Paula Junior et al. 2007). Thus, it appears that the appropriate seeding depth should be concisely detected for each crop and agricultural region according to soil characteristics such as microbial interactions. In regional studies of bean crops cultivated across a highly diverse soil physical and biological properties, shallower planting at a depth of 5 cm strongly restricted charcoal, *Fusarium* (Naseri and Marefat 2011; Gogoi et al. 2018), and *Rhizoctonia* (Naseri 2013b) root rots and improved productivity that were confirmed by plot-scale experiments (Naseri and Mousavi 2013). Further macro-scale findings indicated the noticeable linkage of *Fusarium* wilt epidemics with seeding depth in association with bean market class and previous crop (Naseri and Tabande 2017). Given the noticeable role of seeding depth in root rot control and seed production (Naseri and Marefat 2011; Naseri et al. 2018; Yadav et al. 2018), shallow sowing was recommended to Iranian bean growers as a major strategy for economic and organic production (Naseri and Hemmati 2017). Moreover, this brief review demonstrated that there is a potential to benefit from deep seeding in improving legume productivity and developing more sustainable cropping systems, provided that efficient antagonistic activities against root rot pathogens are present in the soil.

7.7 Root Symbiosis

It is much desired to lower the environmental costs of intensive agriculture through sustainable agronomy practices and improve crop productivity. For this reason, the beneficial ability of leguminaceous crops to provide N_2-fixing symbiosis with soil rhizobia has long attracted the attention of many agronomists. For instance, faba beans provide about 315 kg N ha^{-1} after 110 days of growth (Singh and Bhatt 2012). However, increasing farmers' demands for chemical fertilizers due to N deficiency can postpone achieving sustainable production in legumes. A perfect soil management program can optimize the legume-Rhizobium interplay and thereby improve crop productivity. Such efficient rhizobial nodulation can minimize the demand for chemical N-fertilizers. The inoculation of soybeans with commercially produced rhizobia in Brazil returned the annual savings of $1.3 billion in cropping costs (Coutinho et al. 2000). In the Midwestern United States, the cultivation of corn crops in rotation with alfalfa has created saving of $50–90 million in production expenses (Dias et al. 2014). Rhizobacteria belong to the genera *Rhizobium*, *Sinorhizobium*, *Bradyrhizobium*, *Azorhizobium*, *Mesorhizobium*, and *Allorhizobium* which form N_2-fixing nodules onto legume root systems. These beneficial bacteria are important soil microbiota which provide beans, faba beans, peas, and lupines with 50, 75, 70, and 95% of their N needs, respectively (Werner 1999).

Unfortunately, naturally occurring rhizobia populations with generally poor N_2-fixation efficiency can compete strongly with commercial inoculants. In addition to microbial interrelationships, the effective nodulation by introduced rhizobia is usually associated with a complex of soil attributes (Slattery et al. 2001; Meena et al. 2016b). The linkage of legume-Rhizobium symbiosis with soil moisture (Slattery et al. 2001), clay content (Howieson and Ballard 2004), pH (Slattery et al. 2004; Elias and Herridge 2015), soil depth (Rupela et al. 1987), N-fertilizer (Chemining'wa and Kevin Vessey 2006), soil microbiota (Kalantari et al. 2018), and temperature (Rennie and Kemp 1983) have been earlier documented. The efficiency of the soil biological property is noticeably dependent on greater soil clay contents for rhizobia protection and moisture retention, greater soil residue maintained following no-tillage, sowing in field soil pH at neutral to above-neutral levels, regular cultivation of rhizobia-inoculated chickpea, and avoiding saline soils allowing the development of soil rhizobia communities in chickpea cropping systems (Elias and Herridge 2015; Dadhich et al. 2015). Furthermore, soil populations of these beneficial root symbionts could be increased by sowing chickpeas in highly clayey soils with neutral to alkaline pH and low salinity (Elias and Herridge 2014). The positive effect of soil moisture on rhizobial numbers has been much reported (e.g. Slattery et al. 2001; Elias and Herridge 2015). Moisture content of the soils strongly corresponded with clay content which positively affects rhizobial survival, presumably due to physical protection of bacteria and greater nutrient availability (Issa and Wood 1995; Revellin et al. 1996; Denton et al. 2000; Howieson and Ballard 2004; Kumar et al. 2017b). In addition to moisture factor, Dart and Mercer (1965) demonstrated that temperature significantly affected cowpea nodulation, with an optimum temperature of 24 °C being detected in the glasshouse. Elsewhere, over the hyacinth bean (*Lablab* *purpureus* L.) growing season, a lower nodulation was obtained in winter (January) than in summer (June) when the crop was less sensitive to drought stress and nodulating well (Habish and Mahdi 1976). Therefore, improved nodulation in legumes appears under warmer soil temperatures. The influence of pH on rhizobial populations is also well documented. For instance, soil pH was evidenced as a major determinant of naturally occurring *Rhizobium meliloti* populations (Brockwell et al. 1991). However, Elias and Herridge (2015) found no strong association between soils pH ranging from 6.3 to 8.9 and rhizobial numbers. Likewise, there was no significant relationship between pH of Indian chickpea cropping soils and rhizobial numbers across the pH range 6.4–8.8 (Rupela et al. 1987). In the review of legume-*Rhizobium* symbiosis in interaction with different soil factors, Slattery et al. (2001) discussed decreases in rhizobia populations because of the soil extremes in soil pH (highly acidic or alkaline soils), salinity, high soil temperature, and chemical residues, which commonly occur in cropping systems of southern Australia.

In addition to soil properties, certain agronomic practices have been known as influential factors on effective legume-Rhizobium symbiosis in sustainable agriculture. The cultivation of legume crops has been reported as a well-established strategy to increase soil fertility and decrease the need for chemical N-fertilizers without serious environmental hazards. Growing rotational crops (Kucey and Hynes 1989) with the ability of rhizobial symbiosis have been previously reported. Furthermore, the biological N-fixation and soil fertility following legume cultivation is known as one of such advantageous methods to maximize the amount of crop output per unit of water, N-fertilizer, and fungicide input. Regular sowings of Rhizobium-inoculated chickpea can increase soil populations of these beneficial bacteria in chickpea farming systems (Elias and Herridge 2014). Although Elias and Herridge (2015) reported the considerable impact of planting date on crop water use efficiency and thereby on productivity in Rhizobium-nodulated chickpeas, they did not examine the sowing date-nodulation interaction. In south-eastern Australia, earlier sowing (late April to early May) improved N fixation and total soil N via debris retention in pea crops (O'Connor et al. 1993). This beneficial effect of planting date was attributed to greater pea biomass and higher N concentration coming from efficient rhizobial nodulation. Furthermore, Elias and Herridge (2014) recognized crop available water as a major indicator of chickpea production in Rhizobium-nodulated crops. They also recommended crop residue retention following no-tillage practice for maintaining soil moisture and providing favourable conditions for growth and survival of rhizobia. This advice has been also offered by previous studies (Ferreira et al. 2000; Hungria et al. 2001; Slattery et al. 2001; Kumar et al. 2018b). In India, rhizobial nodulation and groundnut (*Arachis hypogaea* L.) production improved in inoculated plants, and Naidu (2000) recommended post-inoculation seed treatments with benomyl, carbendazim, carbofuran, thiram, and mancozeb which were non-toxic to *Rhizobium* and increased nodulation, dry weight of nodules, and pod yield. He concluded that pesticides, when applied based on standard recommendations, not only do not harm microbial activities but also stimulate nodulation (Naidu 2000). Elsewhere, benomyl reduced bradyrhizobia nodulation by up to 87% in sandy soils without rhizobial inoculations and soybean cultivation at greenhouse and field scales in Brazil (Campo et al. 2009). Ramos and Ribeiro (1993) advised that the inhibitory effect of benomyl on nodulating inoculants disappeared when fungicide-treated seeds were inoculated with rhizobia in seed furrows. Under field conditions, pre-plant applications of herbicides such as trifluralin [α,α,α-trifluro-2,6,-dinitro-N,N-dipropyl-p-toluidine] and metribuzin [4-amino-6-tert-butyl-3-(methylthio)-a5-triazin-5(4H)one] showed no detrimental effect on the growth and N self-sufficiency of faba bean (Bertholet and Clark 1985). Mårtensson (1992) also reported detrimental impacts of over-using bentazone on nodulation by *Rhizobium leguminosarum* bv. *trifolii*.

According to phytotron and field studies, Rennie and Kemp (1983) concluded that symbiotic efficiency is highly associated with N_2-fixing *Rhizobium phaseoli* strain, bean cultivar, mineral N levels, growth habit, growth stage, and temperature. For instance, either temperate or climbing beans provided higher N_2 fixation than tropical and bush cultivars, respectively, depending on *R. phaseoli* strains. A 10% reduction in N_2 fixation due to adding 40 kg ha^{-1} N-fertilizer and also greater N_2 fixation at anthesis than at maturity were dependent on bean cultivar. In the field, nearly half of N need of beans was provided via rhizobial nodulation, with the other 50% being supplied by N-fertilizer and soil N. Depending on the cultivar, 40–125 kg ha^{-1} N was fixed by the bean-rhizobium symbiosis. The similar nodulation efficiency has been reported for the symbiosis of soybeans with *Rhizobium japonicum* (Rennie and Kemp 1983). In southern Alberta, a 4-year comparison of soil populations of *R. leguminosarum* bv. *phaseoli* and bv. *viciae* in bean, pea, and wheat fields indicated that fields cropped to legumes and receiving rhizobial inoculants maintained high populations of rhizobia for several years after harvest of the legume crop even if the field had been cropped to non-legumes or left fallow (Kucey and Hynes 1989).

Although the amount of N fixed by bean under field conditions has been often considered lower than other legumes, the outcome of this symbiotic relationship is highly affected by a diverse range of environmental conditions (reviewed in Giller 2001; Meena and Yadav 2015). Further, the effect of *Rhizobium-Azospirillum* coinoculation on yield of a number of bean genotypes varied across different environments depending on the host genotype (Remans et al. 2008). They suggested that more field-scale experiments, over different seasons and across different environments, are required to describe the interaction between genotype, bacterium, and environment. Soil populations of chickpea rhizobia collected from different geographic areas in India varied by region; however, differences in pH, electrical conductivity, and nitrate-nitrogen status of the soil did not correspond with variability in *Rhizobium* populations (Rupela et al. 1987). In eastern Canada, the population and efficiency of resident *Rhizobium leguminosarum* bv. *viciae* sampled from a broad geographical range of southern Manitoba corresponded with soil pH (6–8) and electrical conductivity (EC; Chemining'wa and Kevin Vessey 2006). They still recommended the use of commercial rhizobial inoculants on pea which improved aboveground dry matter and fixed N up to 29 and 51%, respectively, at only 2 of 10 site-years. Application of 100 kg ha^{-1} N-fertilizer which reduced nodulation at almost all site-years (up to 70%) rarely increased aboveground dry matter compared to inoculated pea crops (Chemining'wa and Kevin Vessey 2006). In southern Australia, communities of naturally occurring rhizobia capable of effective symbiosis with pea, faba bean, lentil, vetch (*Vicia sativa* L.), chickpea, and lupin varied noticeably according to location, soil type, and pH over a range of soil environments. They advised legume growers to use rhizobial inoculation in acidic soils in south-eastern Australia (Slattery et al. 2004; Dhakal et al. 2015). Therefore, improvement of rhizobial nodulation and N fixation which is a major goal in legume cultivation needs a systematic understanding of agro-ecological factors controlling legume-Rhizobium symbiosis in order to maximize symbiosis efficiency for economical and sustainable production. Moreover, a joint comparison of agro-ecological descriptors of seasonal patterns of legume-Rhizobium symbiosis under commercial production conditions allows the future farm-management programs to be more concisely optimized to improve the efficiency of N fixation and sustainability of cropping systems. Furthermore, large-scale findings can extend the applicability of outcomes to other cropping systems different from those studied. In Iran, rhizobial nodulation improved with growing white beans, later sowings in June, lower *Fusarium* root rot index, and the lack of fungicidal treatment of bean seeds and field soil (Naseri's unpublished data). Therefore, providing favourable agro-ecological conditions for symbiotic N fixation will improve legume productivity and soil fertility (Fig. 7.2).

Besides beneficial impacts of rhizobacteria on legume production, the symbiosis of host plant with these soil resident bacteria can restrict the development of root diseases. For instance, inoculation of disease-affected beans with *R. leguminosarum* reduced *Fusarium* root rot by 34.3% and improved plant biomass in India (Hassan Dar et al. 1997). Likewise, *R. leguminosarum* inhibited *R. solani* hyphal growth and suppressed bean *Rhizoctonia* root rot (Ehteshamul-Haque and Ghaffar 1993; ÖzkoC and Delıvelı 2001). Ansari (2010) evidenced that using Zn in combination with

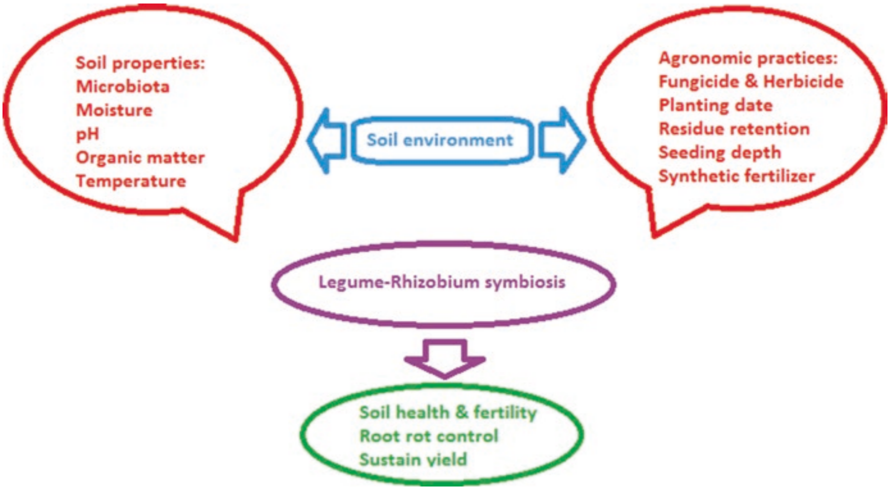

Fig. 7.2 Legume root rots, rhizobial nodulation, and soil environment

Bradyrhizobium japonicum and *T. viride* controlled charcoal root rot. Under greenhouse conditions, liming of acidic soils reduced Fusarium root rot (Tu 1992) and increased bean nodulation and productivity (Buerkert et al. 1990). Elsewhere, the reduction of *Fusarium* root rot and improvement of bean yield due to seed inoculations with *R. leguminosarum* were dependent on the study site and year (Estevez de Jensen et al. 2004). Hassan Dar et al. (1997) noted that differences in the bean-*Fusarium-Rhizobium* interplay are results of variability in soil attributes and genotypic diversity in bacteria, pathogen, and plant across different geographical areas. In agreement with earlier findings, a well-established nodulation by naturally occurring rhizobia in commercial bean crops reduced root rot diseases caused by soilborne pathogens (Naseri 2013a; Naseri and Mousavi 2014; Naseri and Moradi 2014; Meena and Yadav 2014) and enhanced seed production under highly diverse microbial, crop, and environmental properties (Naseri 2014a). It should be noted that further studies recognized *Fusarium* root rot as the third most influential factor on rhizobial nodulation in bean fields among the 20 agro-ecological variables studied (Naseri unpublished data). Kalantari et al. (2018) determined *Rhizobium* sp. as the most predominant rhizobial bacteria in the major bean-growing area of Zanjan, Iran. However, the presence of high nodulation in only 12.3% of the commercial bean fields can be probably attributed to either over-fertilization or Fe deficiency which is a common outcome of calcareous soils of Zanjan (Naseri 2013a) that can lower rhizobial nodulation in legumes and then, in turn, crop development (Slatni et al. 2008). For sustainably improved production perspectives, Naseri and Hemmati (2017) advised Iranian bean growers to reinforce rhizobial nodulation using commercial inoculants or involving potential legume crops into rotation sequences according to macro-scale achievements on beneficial legume-Rhizobium symbiosis.

It is interesting that the extent of benefits from N fixed by legume-*Rhizobium* symbiosis is related to the activity of another important group of root symbionts, known as arbuscular mycorrhizal fungi (Scheublin et al. 2004; Varma et al. 2017b). Exchanging carbohydrates, providing P, and protecting plants against drought and pathogens have been reported as benefits of these mutualistic fungi in the soil (Borowicz 2001). These beneficial fungi can colonize legume roots and nodules that also improve N fixation (Valdenegro et al. 2001). Bagayoko et al. (2000) indicated that rotation with legumes improved root infections by arbuscular mycorrhizae in sorghum crops and thereby productivity. It is evidenced that *Glomus intraradices*, common soil arbuscular mycorrhizae, can protect bean plants against *Fusarium* root rot (Filion et al. 2003). Treatments of bean plants with arbuscular mycorrhizae reduced *Rhizoctonia* root rot under field conditions and improved productivity (Neeraj and Singh 2011; Kumar et al. 2017). There are many reports on the potential of these beneficial soil fungi to cooperate with rhizobial bacteria, control legume root rots, and enhance crop yield. As known, the presence of active arbuscular mycorrhizae in agricultural soils is notably threatened by applications of chemicals (Bainard et al. 2012). Thus, sustainable farming systems should include effective agronomic practices such as mixed cropping and increased C inputs into the soil to improve mycorrhizal colonization which in turn increases N, P, and Zn uptake by roots and promotes soil microbial populations (Zarea et al. 2009; Kakraliya et al. 2018).

7.8 Soil Microbiota

Although the structure of soil microbial communities in agricultural soils is controlled by a complex of factors, plants have been considered as the most important indicator of soil microbiota presence and activities (Garbeva et al. 2004; Meena et al. 2015). According to greenhouse findings, the detection of dense populations of actinomycetes in the rhizospheres of faba beans, peas, and white lupins at maturity stage of growth suggests plowing their debris into the soil as biofertilizers (Sharma et al. 2005). *Pseudomonas fluorescens* is known as one of the most commonly characterized bacteria responsible for soil suppressiveness against fungal plant pathogens (Baehler et al. 2006). In India, bean *Rhizoctonia* root rot in field soil containing low SOC and N, with medium P, was controlled in combined treatments involving arbuscular mycorrhizal fungi (*Glomus sinuosum* and *Gigaspora albida*) and *P. fluorescens* under field conditions. Furthermore, addition of mustard (*Brassica nigra* L.) oil cake (containing glucosinolates and sulphur compounds) to this combined inoculation registered the best treatment for the disease management (Neeraj and Singh 2011). Fluorescent pseudomonads amended with chitin bioformulation exerted direct antagonism against *Macrophomina* root rot, induced resistance mechanisms, and promoted plant growth in Indian mungbeans (*Vigna radiate* L. Wilczek; Saravanakumar et al. 2007). The other PGPR mixtures proved as biocontrol agents in legume root rot pathosystems are as follows: *Pseudomonas* sp. and *Mesorhizobium* sp. against *Pythium* and *Rhizoctonia* root rots in chickpeas (Sindhu and Dadarwal 2001) and *Bacillus pumilus* and *Pseudomonas putida* against pea *Fusarium* root rot (Akhtar and Azam 2014). Because of the expected low compatibility of an individual biocontrol agent applied to highly variable agroecosystems, it is crucial to develop PGPR combinations exerting superior antagonistic effects on root rot pathogens. For instance, the combined application of *B. pumilus*, *Pseudomonas alcaligenes*, and *Rhizobium* sp. provided greater root nodulation and plant production and lentil Fusarium wilt suppression compared to individual and dual inoculations in lentil (Akhtar et al. 2010). In Iran, greenhouse studies indicated that combined inoculation of bean plants with *Bacillus subtilis*, *P. fluorescens*, and *R. Leguminosarum* suppressed *Fusarium* root rot and enhanced crop development and production (Kalantari et al. 2018). This first-time reported compatibility of triple mixture is a prerequisite for the development of more effective biofertilizers or biofungicides for sustainable legume cultivation.

Besides the above-mentioned plant growth-promoting and antagonistic bacteria, soil inhabitant fungi have attracted experts' attention to formulate promising biofertilizers and biofungicides. For instance, Yehia et al. (1988) recommended seed coating with *Trichoderma viride*, which is the antagonist of *Fusarium solani* in faba beans, that improved plant growth and root nodulation. It seems that organic matter sources incorporated into the formulation of biofungicides promote their effectiveness as a biofertilizer. Addition of organic manures to biofertilizers also improved the plant growth and production in vegetables (Shaheen et al. 2007). El-Mougy and Abdel-Kader (2008) evidenced that seed applications of *B. subtilis*, *P. fluorescens*, and *Trichoderma harzianum* controlled pre- and post-emergence root rots in faba

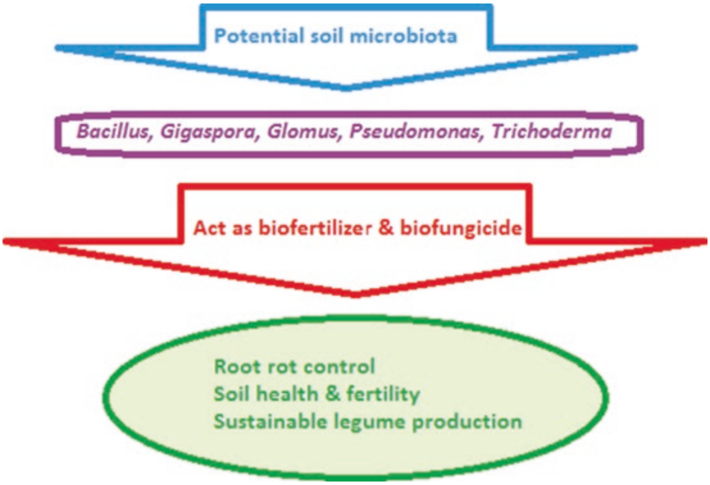

Fig. 7.3 Soil microbiota benefits for agroecosystems

beans tested in the greenhouse and field. In the greenhouse, compatible combination of *Rhizobium* spp. and *Trichoderma* sp. controlled damping off and root rot and then improved seed yield of faba bean, chickpea, and lupine crops (Shaban and El-Bramawy 2011). Furthermore, the most effective antagonist against chickpea *Fusarium* wilt was *T. harzianum* with reducing number of wilted plants by 81% followed by *Penicillium* sp. (71%), *Azotobacter* sp. (63%), and *Rhizobium* sp. (30%) applied as seed treatments under field conditions (Subhani et al. 2013). In Iran, *Trichoderma* spp. were screened for potential antagonism against root rot pathogens in beans (Khodae and Hemmati 2016) and chickpeas (unpublished data) to develop effective biofungicides. Dave et al. (2013) determined that treatments of mustard with *T. harzianum* increased total phenol and protein in the plant. There are competent strains of *Trichoderma* in the rhizosphere that exert mycoparasitism against soilborne pathogens, provide symbiosis relationships with their host plants, enhance plant growth and nutritional absorption, and induce resistance against biotic and abiotic stresses (Shoresh et al. 2010). Thus, concise screening methods are needed to identify such beneficial soil microbiota to be involved into more efficient biofungicides and biofertilizers for economic and organic legume production (Fig. 7.3).

7.9 Soil Moisture and Irrigation Program

Although soil moisture is known as one of the most important factors in plant growth, it is surprising that this plant requirement is often loosely associated with legume root rots which can restrict root growth and adsorption of soil water. For instance, there was no relationship between soil moisture and soybean *Rhizoctonia* root rot in the greenhouse (Dorrance et al. 2003; Yadav et al. 2017b). Furthermore, Paula Júnior et al. (2007) evidenced that different moisture levels ranging from 15% to 42% (v/v) were ineffective on seedling emergence and growth of bean plants grown in *Rhizoctonia*-infested soils. Supporting small-scale studies, large-scale findings from Naseri (2010) also determined no significant association of soil moisture with *Fusarium* and *Rhizoctonia* root rot epidemics occurred in 85 commercial bean fields in Iran, while this soil property directly corresponded with seed production in bean crops (Naseri 2010). Besides the documents on non-significant relation of soil moisture to legume root rots, there have been few contradictory reports such as the strong effect of soil moisture on the size of root lesions induced by *R. solani* (van Bruggen et al. 1986). Radha and Menon (1957) described greater correspondence of *R. solani* with soil microbiota than with high soil moisture levels. Likewise, Paula Júnior et al. (2007) evidenced the stronger suppression of bean *Rhizoctonia* root rot by *T. harzianum* in moist soils. One may conclude that soil moisture can impact the development of legume root rots depending on the soil biological status.

Considering inconsistent associations of legume root rots with soil moisture (Kataria and Grover 1976; Kobriger and Hagedorn 1983; Sneh et al. 1996; Allen and Lenne 1997; Naseri 2010), it is interesting to know how the soil-moisture-associated farmers' practices involved in the field irrigation program interact with the crop disease and production. In attempts to describe the interactions of *Fusarium* root rot and sprinkler irrigation patterns with bean production, Miller and Burke (1986) found that frequent irrigation at 3–5 days' intervals improved productivity of beans grown in *Fusarium*-infested soils, but not in the absence of pathogen. In order to reduce farming expenses, longer irrigation intervals at 8–10 days were recommended in subsoiled bean fields due to the inconsistent association of soil moisture (at 50 and 60% levels) with productivity (Silbernagel and Mills 1990). On a regional basis, irrigation frequency was ineffective on bean yield across highly diverse production conditions (Naseri and Marefat 2011), whereas frequent irrigations at 2–3 days' intervals intensified charcoal, *Fusarium*, and *Rhizoctonia* root rot epidemics compared to those at 4–9 days' intervals (Naseri 2013c; Naseri and Marefat 2011; Naseri and Taghadossi 2014). Thus, considering the lack of linkage between irrigation frequency and productivity, a less frequent irrigation pattern, every 7–9 days, was recommended to bean growers because of the strong correspondence of this farm management practice with root rot diseases and also higher cropping expenses without yield improvements. This large-scale finding, which was confirmed at plot scale (Naseri unpublished data), signifies the importance of applying an appropriate irrigation pattern for economic and organic bean production. Future research may confirm such agronomic advices for other legume crops.

To meet a globalized world's increasing demand for agricultural products, decreasing available water resources, and restricting legume root rots, more conservative irrigation methods should be developed to manage all these farming requirements. Besides non-conservative use of water in agriculture worldwide, furrow and flood irrigations are applied to 95% of bean crops in Zanjan, Iran (Naseri et al. 2016), and 97% of irrigated farming in China (Gleick 2003). In addition to inefficient use of water in such open irrigation systems, they can contribute into introduction and distribution of pathogens like *Fusarium solani* (Shokes and McCarter 1979; Zappia et al. 2014) or increase of root rots due to stressing plants by oxygen limits following the retention of excess water on soil surface (Miller et al. 1980). There are a number of reports on epidemics of aerial diseases such as Sclerotinia blight and pod rot of peanut which are intensified by greater humidity provided via sprinkler irrigation (Porter et al. 1987). Based on large-scale findings obtained by Naseri et al. (2016) and Naseri and Moradi (2015) across highly diverse bean cropping systems, sprinkler irrigation restricted the development of *Fusarium* and *Rhizoctonia* root rot epidemics during the growing season when compared to furrow and flood irrigation systems. This method which is aimed to provide the root system with adequate water also improved seed production by 36 and 56% compared to flood and furrow irrigations, respectively (Naseri et al. 2016). As a conclusion, it seems necessary to optimize irrigation programs in the context of controlling legume root diseases, conservation of water resources, and sustainable crop production.

7.10 Soil Organic Matter

The beneficial impacts of SOM on the biological and physicochemical characteristics of field soil have been long known (Weil and Magdoff 2004). In the light of increasing SOM contents in agricultural soils, a large number of studies have recommended the application of compost to optimize the interaction of the soil environment with crops (Rodd et al. 2002; Rahman et al. 2006; Meena et al. 2017). The noticeable role of compost in slow-releasing major nutrients such as N, P, and K has been well documented in the literature (Sullivan 2001). Soil suppressiveness against soilborne pathogens and thereby improvements of crop yield are also mentioned as benefits of applying adequate SOM to the soil (Weller et al. 2002). Reviewing a large number of previous findings on suppressive capacity of various SOM amendments to soilborne pathogens indicated that compost was the most effective substrate with more than 50% of the case studies achieved disease control outcomes, followed by crop residues (45%) and peat (4%; Bonanomi et al. 2007; Meena et al. 2015c). Tilston et al. (2002) recommended that sufficiently matured compost formulations should have greater extractable C without compromising low levels of nitrate-N or pH ≥7 to suppress soilborne crop pathogens. Alabouvette et al. (2006) also advised enriching composts with competent strains of biocontrol agents in order to improve their suppressive potential.

For another instance, green manures decreased *Fusarium* root rot epidemics (Tu 1992). However, it should be noted that *R. solani* saprophytically colonizes fresh organic matter and green manure and then survives on them (Chauhan et al. 2000; Wale 2004). Applications of swine manure can increase predominant soil inhabitant microorganisms in particular populations of *Trichoderma* spp. with biocontrol attributes (Conn and Lazarovits 1999). Blair (1943) demonstrated that SOM reduced *R. solani* survival as a result of moisture retention in the soil. Furthermore, the composition of organic amendments also appears influential on soilborne pathogens. For instance, larger populations of soil antagonists because of the crop residues of bean, buckwheat (*Fagopyrum esculentum* Möench), maize, oats, and Sudan grass

(*Sorghum vulgare* Pers.) suppressed *Rhizoctonia* root rot in snapbeans (Papavizas and Davey 1960). In addition, applications of farmyard manure, neem (*Azadirachta indica* A. Juss.), or mustard cake were recommended for efficient control of *Macrophomina* root rot (Rathore 2000). Lodha et al. (2002) also added that soil applications of pearl millet (*Pennisetum glaucum* (L.) R. Br.) compost reduced plant death by 63–72% in cluster beans (*Cyamopsis tetragonoloba* (L.) Taub.) infected by *M. phaseolina*. To improve the efficiency of organic amendments, it has been suggested to integrate this soil management strategy with supportive cultural practices such as liming, fertilization, crop rotation, deep ploughing, adequate irrigation, and planting density to control *Macrophomina* root rot in sunflower and sorghum (Collins et al. 1991; Ploper et al. 2001; Yadav et al. 2017a). Naseri (2014a) determined a 50% lower *Fusarium* root rot and twofold greater yield for beans commercially grown in soils containing 1.2–1.8% SOM compared to the lower level (0.4–0.8%). Furthermore, this soil attribute studied across a highly diverse agroecological conditions played a magnificent role in restricting the development of *Rhizoctonia* and *Macrophomina* root rot epidemics over the growing season (Naseri 2013a; Naseri and Moradi 2014). Such important associations recognize the optimization of SOM content as a major part of farming programs to be organized for bean-growing areas such as Zanjan with only 9.8% of field soils containing 1.2–1.8% SOM. Supporting previous documents, these large-scale findings obtained from a diverse range of agronomic and environmental properties confirm that the improvement of SOM should be considered in sustainable agronomy and production of bean crops. These achievements also offer great hope for gaining similar benefits from sufficient SOM to soilborne diseases and legume productivity from economic and organic viewpoints (Fig. 7.4).

7.11 Soil pH

Because of the association of soil pH with various farm management practices such as liming, urea fertilization, and manure application (Stevens et al. 1998), a unified sight into the legume root rot-pH interplay is still lacking. Simek et al. (2002) reported neutrality as the optimum pH for evolution of denitrification products presumably as a result of the development of larger communities of denitrifiers at the neutral pH. Considering the potential of denitrifier bacteria in disease suppression and yield improvement (reviewed in Sect. 7.7. ‘Root Symbiosis’), this larger population of such beneficial symbionts in the neutral soil may explain why liming of acidic soils restricted *Fusarium* root rot in the greenhouse (Tu 1992) and improved bean productivity (Buerkert et al. 1990). In a non-legume-*Fusarium* pathosystem, soil suppressiveness against flax (*Linum usitatissimum* L.) *Fusarium* wilt corresponded with soil pH and communities of fluorescent pseudomonads, with suppressiveness being highest at the neutral pH (Höper et al. 1995). Thus, like denitrifier bacteria exerting symbiosis with different legume crops, the domination of this group of beneficial bacteria belonging to *P. fluorescens* restricts the density of root rot pathogens and reduces the disease development in the neutral soil (reviewed in

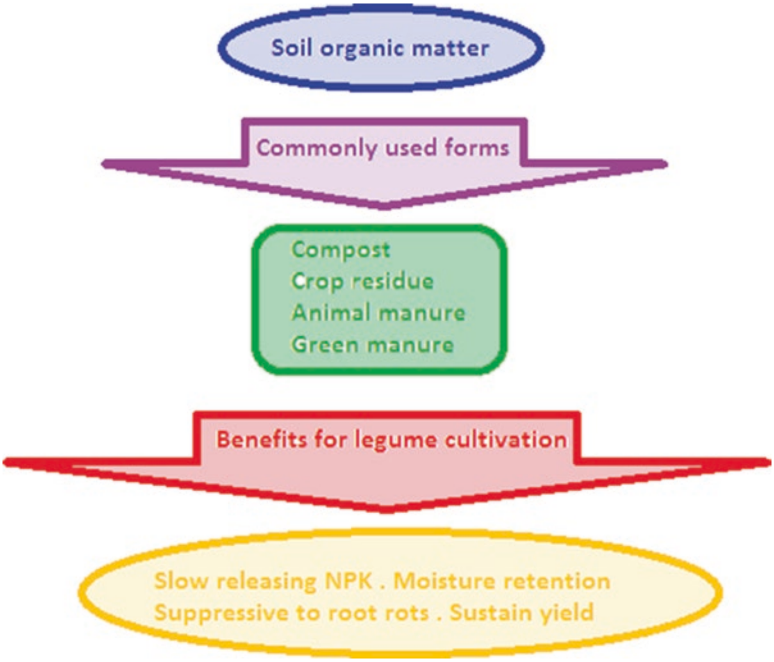

Fig. 7.4 Soil organic matter, agroecosystem, and legume root rot

Sect. 7.8. ‘Soil Microbiota’). This should be also added that greater pH levels limit the accessibility of *F. oxysporum* to micronutrients needed for propagation and pathogenesis (Jones et al. 1989). Naseri (2014a) demonstrated that even a narrow range of soil pH varying from neutral (7) to alkaline (8) restricted the late-season development of bean *Fusarium* root rot epidemics that occurred across wide ranges of soil biological and physico-chemical properties. For this reason, Naseri and Marefat (2011) attributed the overuse of urea by majority of bean farmers in Zanjan that could have presumably resulted in soil acidification and disappearance of alkaline-pH benefits (Sullivan 2001) to the outbreaks of *Fusarium* root rot in beans. Moreover, this is presumably why bean yield did not improve in alkaline soils of Zanjan’s main bean-growing area (Naseri and Marefat 2011; Dhakal et al. 2016). Naseri (2014a) observed that soil pH as high as 8 favoured early season development of *Rhizoctonia* root rot in commercial bean crops. To be more accurate, the higher level of soil pH, 7.5–7.9, increased the disease prevalence by 24.3% compared to the lower pH range of 7.0–7.5 (Naseri 2014a). However, this association disappeared when the linkage of soil pH to the overall development of *Rhizoctonia* root rot epidemics over the growing season was examined. This may suggest that such notable interaction of soil pH with the disease development has been affected by agricultural practices conducted over the growing season. It should be added that Kataria and Grover (1987) reported more severe *Rhizoctonia* root rot of mung bean in neutral and alkaline soils than acidic soils. An earlier laboratory examination also indicated better growth of *R. solani* on agar at pH 6.5–7.5 compared to the pH range of 3.5–8.5 (Chet and Baker 1980). In the greenhouse, liming of autoclaved pot soil up to pH 5.9 increased bean *Rhizoctonia* root rot by 32% compared to pH 4.9 (Rodrigues et al. 2002). Although there are reports on non-significant association of bean *Fusarium* root rot with soil pH under greenhouse and field conditions (e.g. the report from Schuerger and Mitchell 1992), this soil factor often appears influential on legume root rots. The large-scale study of soil pH in association with the bean-*Macrophomina* pathosystem showed that pH levels as high as 8 favoured epidemics of charcoal root rot at pod maturity (Naseri 2014b; Meena et al. 2017b). Likewise, in the United Kingdom, pea *Fusarium* root rot was linked positively to pH levels of commercial field soils (Etebu and Osborn 2012; Meena et al. 2015b). In Iran, Naseri (2014c) evidenced more intense epidemics of *Fusarium* wilt for the soil pH at 8 in commercial bean crops. In the light of population densities of root rot pathogens in legume field soils, there was neither association between pH (6.0–7.5) and soil populations of *F. solani* f. sp. *glycines* in commercial soybean fields (Scherm et al. 1998) nor significant impact of the acid soil (pH 4.5) on survival of *M. phaseolina* microsclerotia (Papavizas 1977). However, soil pH noticeably corresponded with soil populations of *F. oxysporum*, *M. phaseolina*, and *R. solani* in commercial bean fields (Naseri and Hamadani 2017). Besides the direct or indirect associations of root rot pathogens populations with the soil pH, the total soil population of pathogens decreased with increasing pH from 7 to 8 (Naseri 2016; Naseri and Hamadani 2017). As a conclusion, any agronomic strategy such as the overuse of urea which acidifies field soils should be avoided in legume cropping systems to benefit from neutral-alkaline pH promoting soil suppressiveness against soilborne pathogens and improving productivity from organic and economic viewpoints.

7.12 Soil Structure

It is quite generally believed that root development and diseases are associated with soil texture and structure (Table 7.1) which influence soil porosity, water retention, and mineral status of soils (Ghorbani et al. 2008; Verma et al. 2015c). For instance, low SOM content and poor moisture-holding capacity in sandy soils were recognized as responsible factors for more severe epidemics of charcoal root rot in bean crops (Lodha et al. 1990). Soybean sudden death syndrome (caused by *F. solani* f. sp. *glycines*) was also increased by nearly fourfold due to the increase of soil sand from 53% to 100% (Sanogo and Yang 2001). Sandy loam soil reduced the plant growth and yield of *Fusarium*-root-rot-affected beans when compared to clay-loam soil (Tu 1992). In agreement with these small-scale findings, greater sand content of the soil and lower clay strongly intensified the early- and late-season development of bean charcoal root rot epidemics across various agro-ecological conditions (Naseri 2014b). Furthermore, greater soil sand and lower silt corresponded with more severe mid- and late-season *Rhizoctonia* root rot epidemics developed in commercial bean farms (Naseri 2013a) that agree with previous small-scale findings (Alabouvette et al. 1996; Gill et al. 2000). In addition, greater sand and silt contents

Table 7.1 Interactions of soil structure with legume root rots

Interaction	References
Low organic matter and moisture retention of sandy soils	Lodha et al. (1990), Ghorbani et al. (2008)
Greater sand content favours root rots	Alabouvette et al. (1996), Gill et al. (2000), Sanogo and Yang (2001), Naseri (2013a, 2014b)
Sandy soils reduce yield	Tu (1992), Naseri (2014a)
Silty or clayey soils suppress root rots	Alabouvette et al. (1996), Gill et al. (2000), Chauhan et al. (2000), Nerey et al. (2010), Naseri (2013a), Naseri and Tabande (2017), Naseri et al. (2018)
Silty or clayey soils favour root rots	Kataria and Grover (1987), Naseri (2014a, 2014c)
Soil compaction and microbiota influence root rots	Lodha et al. (1990), Wale (2004), Harveson et al. (2005), Ghorbani et al. (2008), Nerey et al. (2010)
Silty soils reduce yield	Naseri (2014a)

appeared to decrease productivity in beans (Naseri 2014a). It has been earlier documented that tillage, soil compaction, microbial populations, and moisture retention impact the interactions of bean root rots and yield with soil type (Lodha et al. 1990; Wale 2004; Harveson et al. 2005; Ghorbani et al. 2008; Nerey et al. 2010; Meena et al. 2018b). For instance, Alabouvette et al. (1996) noted that the unstable structure of silty soils can be suppressive to *Rhizoctonia* root rot as a result of greater compaction, less aeration, or more wetness. According to large-scale observations, Naseri and Tabande (2017) added the noticeable dependence of soil clay content in interaction with bean *Fusarium* wilt on the cultivation method, manual or mechanical sowing. Naseri (2014c) also evidenced the dependence of soil silt to the depth of seeding in the bean-*Fusarium* wilt pathosystem under commercial production conditions. Then, Naseri et al. (2018) also demonstrated the noticeable association of soil clay content with bean charcoal root rot that was dependent on soil pH. In contrast to the suppressiveness of silty soils to *Rhizoctonia* root rot (Alabouvette et al. 1996; Gill et al. 2000; Naseri 2013a), greater silt content of field soil intensified epidemics of *Fusarium* wilt and root rot in bean crops (Naseri 2014a, c). Höper et al. (1995) reported that communities of fluorescent pseudomonads, soil texture, and pH were responsible for the suppression of flax *Fusarium* wilt, so that soil suppressiveness increased due to adding clay and increasing soil pH from 4 to 7. Although the suppressiveness of clay content of soils against *Rhizoctonia* root rot has been often documented (Chauhan et al. 2000; Gill et al. 2000; Nerey et al. 2010), adding clay to sandy soils increased *Rhizoctonia* root rot of bean in India (Kataria and Grover 1987). Naseri and Hamadani (2017) demonstrated the significant associations of soil texture with highly heterogeneous soil populations of root rot pathogens in bean fields (Naseri and Mousavi 2015; Sihag et al. 2015). These remarkable relationships of soil population of pathogens, root rot diseases, and bean production to soil texture fractions across a diverse range of cultivation method, microbiota, tillage, soil compaction, SOM, pH, and moisture levels suggested careful optimization of sustainable farm management programs according to soil type.

7.13 Seed and Soil Treatment with Fungicides

Phillips (1989) believed that the development of root rot diseases is highly dependent on practicing those cropping strategies which optimize agroecosystems for crop establishment and production. For instance, fungicidal treatment of lupin seeds suppressed *Rhizoctonia* root rots at field-plot scale (Sweetingham 1990). Elsewhere, the treatment of bean seeds with fungicides improved plant emergence by reducing seedling death (Dorrance et al. 2003) and root rot diseases (Valenciano et al. 2006). In bean field, chemical seed treatment with carbendazim provided the greatest level of root rot suppression in comparison to control plots (Joshi et al. 2009). Treatment of lentil seeds with tebuconazole and metalaxyl was useful to minimize yield losses from *Fusarium* root rot (Hwang et al. 2000). However, treatment of soybean seeds with either carbendazim + thiram or carboxin + thiram and commercial inoculants containing *Bradyrhizobium elkanii* and *B. japonicum* in a field soil with a low SOM content reduced root nodulation (Zilli et al. 2009; Meena et al. 2015e). Furthermore, treating seeds with carbendazim + thiram and *B. elkanii* decreased nodulation by approximately 50% and crop yield by at least 20%. Likewise, laboratory, greenhouse, and field experiments proved that seed treatments with fungicides benomyl, captan, carbendazim, carboxin, difenoconazole, thiabendazole, thiram, and tolylfluanid severely reduced rhizobacterial survival on seeds and root nodulation in soybeans (Campo et al. 2009). Although *T. harzianum* and *T. viride* were compatible with a number of herbicides, fungicides, pesticides, and botanicals, some chemicals such as captan, tebuconazole, vitavax, propiconazole, and chlorothalonil inhibited the growth of these beneficial soil antagonists under in vitro condition (Bagwan 2010). They suggested that seed treatment or furrow applications of the antagonistic fungus could be compatible with thiram, copper oxychloride, mancozeb, herbicides, pesticides, neem cake, oil or leaf, wild sorghum leaf, and mustard cake extracts to manage soilborne diseases of groundnut. In attempts to characterize the interaction of *Fusarium* (Naseri et al. 2016) and *Macrophomina* (Naseri and Moradi 2014) root rot epidemics with fungicidal seed treatment in commercial bean farming systems, notable disease suppression and yield improvement were detected for fungicide-treated seeds. Although fungicidal treatment of legume seeds is recommended to lower chemical use and expenses in comparison with soil fungicidal treatments (Naseri and Hemmati 2017; Verma et al. 2015a), further non-chemical seed treatment solutions are needed to avoid detrimental effects of synthetic fungicides on root nodulation and subsequently on crop protection and production from sustainable agriculture viewpoints.

Since inhibition of beneficial soil microbes can counteract advantages derived from protecting plants from abiotic and biotic stresses, numerous old documents demonstrate adverse effects of synthetic fungicides on mycorrhizal development. For instance, soil drenches of benomyl prevented improved plant growth due to vesicular-arbuscular mycorrhizae in pot experiments (Bailey and Safir 1978). Elsewhere, fungicides benomyl, captan, and PCNB applied to pot soil inhibited colonization by arbuscular mycorrhizal fungi in pea roots (Schreiner and Bethlenfalvay 1997). In addition to mycorrhizal fungi, extensive use of fungicides like benomyl and mancozeb can restrict the communities of other soil antagonistic fungi such as *Trichoderma* spp. (McAllister et al. 1994; McLean et al. 2001). Furthermore, benomyl not only allows the growth of *F. solani* f. sp. *phaseoli* on both cultural media and the soil (Richardson 1973) but also induces the resistance of fungal pathogens to fungicides (Carling et al. 1990; Weiland and Halloin 2001). These detrimental effects of fungicides may have been responsible for the remarkable linkage of soil treatment with fungicides in particular benomyl in 122 commercial bean fields to *Fusarium* and *Rhizoctonia* root rot epidemics (Naseri 2013a, 2014a, 2016). Therefore, in contrast to the old document on effective control of *Rhizoctonia* root rot in mung beans using benomyl (Kataria and Grover 1976), the application of fungicides appears to be an ineffective and non-economic strategy to protect the extending root system from root rot pathogens (Abawi 1989). As a conclusion, legume growers are recommended to avoid applications of fungicides in order to benefit from soil symbionts and antagonists for sustainable legume protection and production.

7.14 Weed Management

Herbicide stress has been generally reported as an effective factor on root infections by soilborne pathogens. Conflicting reports on the effect of herbicides on the infection of legumes by root rot pathogens appear to suggest that the crop-disease-weed interaction is strongly influenced by a wide array of agro-ecological properties (Table 7.2). For instance, soil application of trifluralin in the greenhouse and field intensified soybean *Fusarium* wilt presumably due to swelling and cracking of hypocotyls (Carson et al. 1991), whereas there were inconsistent interactions of trifluralin with growth or reproduction of *F. oxysporum* examined in vitro (Carson et al. 1991). Elsewhere, the application of this herbicide to clayey soils enhanced the production and germination of *F. oxysporum* chlamydospores (Tang et al. 1970). It was previously documented that paraquat reduced *Rhizoctonia* foliar blight of soybean (Black et al. 1996), whereas another herbicide, trifluralin, enhanced the

Table 7.2 Effects of weed management on legume root rots

Interaction	References
Herbicide stress favours root rots	Tang et al. (1970), Mussa and Russell (1977), Wrona et al. (1981), Carson et al. (1991)
Herbicide reduces root rots	Canaday et al. (1986), Naseri (2014b), Naseri and Moradi (2015), Naseri et al. (2016)
Herbicide decreases root symbiosis	Abd-Alla et al. (2000), Niewiadomska and Klama (2005)
Herbicide improves yield	Naseri et al. (2016)

susceptibility of bean plants to *Rhizoctonia* root rot (Wrona et al. 1981). Another study evidenced that applications of trifluralin and bentazon increased *Fusarium* root rot on potted beans when weeds were absent (Mussa and Russell 1977). In the *Macrophomina*-soybean pathosystem at field-plot scale, trifluralin significantly lowered root colonization by the pathogen (Canaday et al. 1986). This observation was supported by Naseri's (2014b) findings obtained under highly heterogeneous agricultural practices, soil environments, pathogen populations, and bean genotypes in commercial fields receiving often trifluralin which corresponded with lower levels of *Macrophomina* root rot epidemics. Further in Iran, attempts were made to describe whether applications of farmers' choice herbicides intensify bean root rots by exerting herbicide stress on roots or control the disease by reducing weed plants as probable pathogen harbors and crop competitors. They suggested that the lack of herbicide applications may have resulted in increases in the population of weeds and in turn more intense *Fusarium* (Naseri et al. 2016) and *Rhizoctonia* (Naseri and Moradi 2015) root rot epidemics, considering the documents evidencing more intense root rots in weedy bean farms (Naseri and Marefat 2011; Naseri 2013b; Meena et al. 2017c). Furthermore, epidemics of *Rhizoctonia* root rot remained unchanged over the growing season in commercial fields receiving trifluralin; however, the disease decreased over time with the application of other herbicides mostly paraquat followed by bentazon (Naseri and Moradi 2015). Although the late-season evaluation of herbicide application at large scale indicated no significant difference in *Fusarium* wilt epidemics between bean fields receiving either no herbicide, trifluralin, or other herbicides (Naseri 2014c), this farmers' practice influenced populations of *F. oxysporum*, *F. solani*, and *M. phaseolina* in field soils (Naseri and Hamadani 2017). Naseri et al. (2016) also attributed improvements of seed production for trifluralin applications to lower weed competitors of bean crops due to herbicide usage. Such a systematic understanding of the herbicide-pathosystem-weed interrelationship can assist with minimizing different abiotic and biotic risks in bean cropping systems. However, it should be also noted that many previous studies have reported the detrimental impacts of synthetic herbicides on legume nodulation. For instance, herbicides afugan, brominal, and gramoxone applied to field soil inhibited root nodulation and colonization by arbuscular mycorrhizal fungi of legumes cowpea, bean, and lupin in the greenhouse (Abd-Alla et al. 2000). Likewise, herbicide imazethapyr decreased nitrogenase activity, nodulation, and root growth induced by rhizobial symbionts of clover, lucerne, and serradella (Niewiadomska and Klama 2005). Therefore, although the herbicidal control of weeds restricted bean root rots and enhanced yield (Naseri 2014b; Naseri and Moradi 2015; Naseri et al. 2016; Naseri and Hemmati 2017; Ram and Meena 2014), sustainable weed management strategies supporting legume nodulation are needed to be incorporated into future farming programs for economic and organic production.

7.15 Future Perspectives

The worldwide increasing demand for food crops can increase environmental pollution due to intensive applications of chemical fertilizers, herbicides, fungicides, and pesticides. Therefore, there is an urgent need to develop more influential crop, disease, and soil management programs according to sustainable legume production principles. To restrict root rots in legume crops and benefit from root symbiosis interactions, proper planting date and depth, sufficient seeding rate, minimum use of chemical fertilizers and herbicides, appropriate crop sequence, applications of biofertilizers and biofungicides, adequate irrigation, and improvement of SOM must provide better food security and sustainability in cropping systems. This will also ensure sustained profitability and save agroecosystem for future uses.

7.16 Conclusion

The present discussion integrates highly diverse findings obtained worldwide at different scales of studies on strategies to manage legume root rots. Such improved insight is greatly helpful to organize more efficient sustainable disease management programs in the future. Therefore, the integration of avoiding fungicidal treatment of soil, enhancing rhizobial nodulation, minimizing chemical fertilization, optimizing soil content of organic matter, planting beans at appropriate date and depth, applying suitable rotation and irrigation programs, and weed management could provide environment-friendly-based disease control programs in legume cropping systems.

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Fate and Behavior of Pesticides and Their Effect on Soil Biological Properties Under Climate Change Scenario

8

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Abstract

Global climate change has imparted inevitable footprints on the environment associated with extreme temperature and rainfall event along with rise in atmospheric carbon dioxide (CO_2) concentration which may notably alter the use, distribution, and degradation patterns of pollutants like pesticides. Environmental fate and behavior of pesticides are controlled by weather parameters like rainfall, temperature, and wind extreme. Climatic events have definite role in controlling the fate of pesticides. Scare information is available in consolidated manner addressing the issues of impacts of climate change on pesticides fate which we have in sighted in this chapter. In this chapter, the main research findings in this field are summarized, and the effects of climate changes on fate, behavior, and transport of pesticides are reviewed. This chapter also summarizes the primary pesticide fate models and their application to assess the impact of climate change. In additionally, research gaps and future research directions are identified and suggested. Under the influence of climate change, global cycling of pesticides has also been discussed which shows that degradation pathway of pesticides is changing with changes in temperature. Due to changes in frequency of freezing and thawing, equilibrium between sorbed and nonsorbed pesticides will be affected and thereby change the degradation, leaching and runoff. Occurrence of frequent heavy rainfall events leads to more runoff and leaching of pesticides and consequent contamination in groundwater and surface water. Due to extreme weather condition, crops are more vulnerable to pest and diseases and frequency and amount of pesticide used is also increased. Though increased temperature or salinity will enhance the degradation of pesticides, production of more toxic metabolites toward aquatic organism is of concern. Understanding of the possible impacts of extreme climatic events on pesticides contaminated soil and possible remediation technologies have also been discussed. Futures research should also be focused on climate change-induced pesticide pollution on air and consequents effect on human health. Moreover, understanding the impacts of climate change on fate and behavior of pesticides is a complex process, and therefore interdisciplinary scientific study on global scale in a long-term basis is the need of the hour.

Keywords

Climate change · Pesticide fate · Pesticide modeling · Precipitation · Salinity · Soil microbial activity · Temperature

Abbreviations

CO_2	Carbon dioxide
EPIC	Erosion-productivity impact calculator
FMO	Flavin-containing monooxygenases

GCC	Global climate change
GUS	Groundwater ubiquity score
IPCC	Intergovernmental Panel on Climate Change
log K_{ow}	Octanol-water partition coefficient
MBC	Microbial biomass carbon
POPs	Persistent organic pollutants
SLR	Sea level rise

8.1 Introduction

Producing more food for increasing global population in a sustainable way with the finite resources is the main herculean task faced by us in today's world (Schneider et al. 2011). These challenges will experience a more competition for water, energy, and land resources as a consequence of global climate change (Godfray et al. 2010). Global climate change (GCC) is linked with significant changes in long-term weather characteristics and short-term extremes weather in different regions. Changes in atmospheric CO_2 concentration, alteration of global temperature, and precipitation resulted in rising sea level and salinity, changes in arable land, crop yield alteration, changes in soil quality, and plant diversity (Jackson et al. 2011) (Table 8.1). With the current rate of atmospheric CO_2 increment, predicted atmospheric CO_2 concentration by 2050 will be 550–700 ppm and almost 650–1200 ppm by the year 2100 (Higgins et al. 2015). This high concentration of atmospheric CO_2 will also lead to high temperature incidence, and predicted temperature rise by 2050 is almost 2.5 °C which may extend up to 6.4 °C by the end of the twenty-first century (IPCC 2007).Temperature from the year 1983–2012 was the highest ever for 1400 years ago, and impacts are more in the Northern Hemisphere (IPCC 2013; 2014). This temperature rise leads to the increase in the rate of glacier melting- and consequently sea level rising-related changes in global water cycling (Meehl et al. 2005; Vermeer and Rahmstorf 2009; Ashoka et al. 2017). While higher latitudes experienced flooding rains, prolonged periods of drought are experienced in semiarid region. Frequent intense tropical cyclones and moving of extratropical storm toward the poles are also predicted (IPCC 2007).

Table 8.1 Climate change impact projections

Climatic parameters	Climate change projections
Mean temperature change	↑ in the tune of 1.1–6.4 °C
Sea level change	↑ in the tune of 0.18–0.59 m
Precipitation	↓20% to ↑20%
Ocean acidity	↑ in the tune of 0.14–0.35 pH units
Sea ice cover change	↓ in Arctic and Antarctic
Ocean circulation	↑ and ↓in ocean currents and circulation pattern
Wind fields and wind speed	↑ and ↓in mean wind speed by 10–20% and change in wind direction

Nowadays, the world is engaged in the gigantic task of feeding over 7.6 billion people which requires continuous efforts to increase food production by use of high-yielding varieties, proper nutrient management, and pest control. The control of economically important insects, weeds, fungi, and other pests are of utmost need of the hour to increase the food production. In order to achieve the objective of maintaining the quantity and quality of agricultural production, pesticide use in agriculture and public health sector is imperative. Pesticides have become an integral part of commercial agriculture. Because of cost-effectiveness, use of these pesticides is likely to remain an inevitable strategy for crop production (Gupta 2004; Yadav et al. 2018b).

Xenobiotics like pesticides have become a major concern as their fate define the quality of our surrounding environment. It is obvious that the major climate change will affect the pesticide use. Environmental persistence and mobility of pesticides are influenced by weather parameters like temperature, rainfall, and wind action (Sarmah et al. 2004; Lewis et al. 2016; Kakraliya et al. 2018). The fate of pesticides in terms of degradation, emission and re-emitting behavior, transportation, source and sink relationship, bioavailability, transfer, and toxicity through food chain is all closely related to climate change. The use of pesticides may also be increased due to climate change as crop will experience more stress due to possible increased pest and disease incidence, and on the other hand, efficacy of the pesticides will reduce due to its high degradation under changing climate scenario (Schiedek et al. 2007; Delcour et al. 2015). Pesticide degradation pathways may be affected by the changes in climate, and consequently production of more toxic metabolites may lead to harmful effects on human and aquatic health. There are chances of more frequent detection of pesticides in groundwater and surface water due to climate change along with high leaching of pesticides (Bloomfield et al. 2006).

Though ample amount of information is available about the fate of persistent organic pollutants (POPs) under climate change scenario, cumulative information on pesticides is scare. According the UN Stockholm Convention (UNEP 2010), POPs also include organochlorine pesticides, like dichlorodiphenyltrichloroethane (DDT) and toxaphene, and their fate under climate change scenario has been discussed elaborately. However, intensive use of pesticide like as atrazine, aldicarb, and chlorpyrifos has increased tremendously, and cumulative information about the fate of these pesticides under changing climatic scenario is not available.

Ultimate storehouse for globally used pesticides is soil, and biological degradation is the major route of pesticide degradation in soil. This helps in predicting the pesticide leftover in soils and allows assessing pesticide exposure-associated risk. In addition, how pesticide will affect the soil ecology under changing climate is also important as it assesses the ecological toxicity of agrochemicals to soil health. Similarly, how to mitigate the adverse impacts of pesticides on soil health under changing climate scenario is also important. This chapter presents an outline about how the changed environmental parameters like atmospheric CO_2 concentration, temperature, rainfall, and salinity may affect the fate and behavior of pesticides and also their effects on soil biological properties and toxicity to other organism. The probable mitigation action to counter the harmful impact of pesticides under climate change scenario particularly on soil health based on available research has also been discussed.

8.2 Interaction of Climate Change with Pesticides

Global climate change is the most acute problem in today's world. Every aspect of our life from the production of food to future development and from the biomass distribution to the level of biodiversity is most studied under climate change scenario but less understood. Earth is experiencing constant and regular changes in its climate over the last century, and we have experienced a warming environment in the last 50 years. Anthropogenic activities are directly related to this situation (Meinshausen et al. 2009; Yadav et al. 2018a). Use of pesticides is the unavoidable step in modern intensive agricultural practices, and climate change has an effect on both pesticide use and pesticide losses to the environment (Koleva and Schneider 2010). Under changing climate scenario, the incidence like drier dry month, wetter wet month will increase and extreme rainfall and temperature event will also likely to increase (Shen and Wang 2013; Verma et al. 2015a).

There will be higher losses of pesticides to the environment under changing climate event. The reasons may be enhancement of rainfall frequency and intensity which resulted in high risk of leaching losses through macropores in the soil, and also the high-intensity rainfall events increase the losses of pesticides through surface runoff (Steffens et al. 2015*)*. Rainfall-induced pesticide leaching sometimes could counteract by temperature-induced higher degradation rate. However, sometimes higher temperature may lead to extreme drought situation, which would slow down the pesticide degradation (Schiedek et al. 2007; Noyes et al. 2009; Dhakal et al. 2015). Figure 8.1 depicted how different closely associated interacting phenomena affect the pesticide's fate and behavior in the environment. Pesticide binding ability of soil organic matter is well known which reduces the leaching of pesticides (Stenrød et al. 2008). However, warmer climate led to high

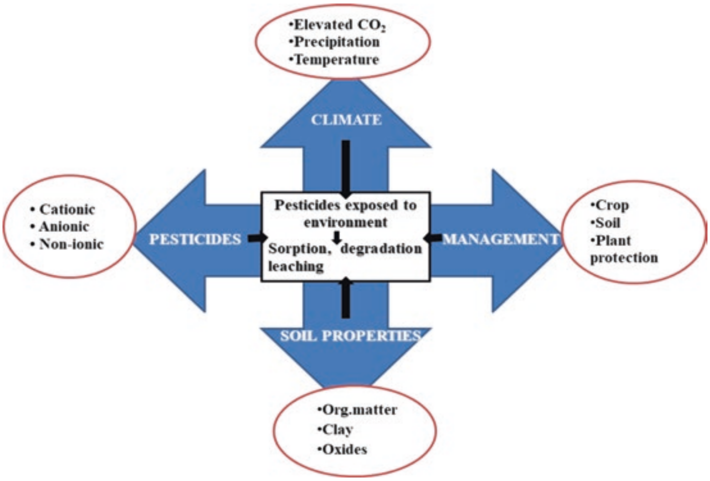

Fig. 8.1 Interacting phenomenon affecting the fate of pesticides under climate change scenario

temperature-induced breakdown of organic material and thus may reduce its contaminant binding ability. So, predicting the fate of pesticides is very difficult due to the interaction of effect of these different variable parameters. Frequent changes of freezing and thawing will affect the equilibrium between sorbed and nonsorbed pesticides and thereby change the availability of pesticides for degradation, leaching, and runoff (Bøe 2017). Other than these direct effects, climate change may result in a longer crop growing season where applied pesticides may get sufficient time to degraded. However, increase in crop growing season in rainy months may increase the leaching event as the frequency of rainfall event is predicted to be increased. Climate change is also influencing the agronomic package of practices of crop which also leads to changes in the type and amount of pesticides needed and thus their fate (Delcour et al. 2015; Dadhich and Meena 2014). High rainfall and temperature event may increase the pests and disease incidence and may also alter the weed flora, which is predicted to increase the use of pesticides. So, in temperate climate, frequent use of herbicides may be changed in the future to greater use of insecticides and fungicides. Changing climate induces alteration in microbial community, and functional structure of soil definitely affects the microbial degradation network of pesticides. However, the relationships are complex, and a good database for evaluating many of the relationships is still lacking (Chakraborty et al. 2000; Boland et al. 2004).

8.3 Climate Change and Pesticide Degradation

8.3.1 Impacts of Increased CO_2 on Pesticide Degradation

Global climate change is likely to affect plant carbon assimilation, growth, biomass allocation, and nutrient uptake. The current atmospheric CO_2 concentration is almost 394 ppm (NOAA, Mouna Loa data, June 2011; Kumar et al. 2018a). During the last decade, the average increment rate of atmospheric CO_2 concentration was almost 1.9 ppm $year^{-1}$ and the predicted CO_2 level by 2050 is 570 ppm. It has also been reported that from year 1953 to 2003, the increase in CO_2 was about 64 ppm (Krull et al. 2005). As a consequence of atmospheric CO_2 increment, Earth's average temperature is also predicted to be increase. Under climate change scenario, rising atmospheric CO_2 is one of the important global issues. From the emergence of industrial revolution, atmospheric CO_2 concentration increased almost by 37%. The possible reason for this increase in atmospheric CO_2 is largely due to combined effects of fossil fuel combustion, forest land clearing, and human activities, which compelled us to develop a thorough understanding of environmental fate of xenobiotics like pesticides.

Soil acts as the sink for majority of the pesticide applied to the crops. Major metabolic pathway responsible for detoxification of pesticides in soil is the microbial degradation. Elevated CO_2 has an impact on soil microbial activity, and thus indirectly it will affect the pesticide degradation. Climate change may alter the volatility, deposition, and degradation properties of pesticides and thus influence the fate and behavior of pesticides in the environment (Noyes et al. 2009; Datta et al. 2017a). Scarce information are available on the elevated CO_2 impacts on pesticide fate. Reports are available only on modeling of the available data to predict the fate of pesticides under future atmospheric CO_2 increasing scenario (Williams et al. 1992; Bailey 2003; Bloomfield et al. 2006). Williams et al. (1992) used the Erosion-Productivity Impact Calculator (EPIC) model to estimate pesticide losses due to weather variation. They predicted that reduced relative humidity or rainfall intensity decreases the losses of atrazine herbicide. However, they predicted the slight losses of atrazine when atmospheric CO_2 increased from 300 to 660 ppm. An herbicide degradation model was developed by Bailey (2003) by using real-time weather data from 1980 to 2001 to determine the alteration in persistence of autumn-applied herbicide isoproturon. The study reported that almost 25% decline in weed control of herbicide isoproturon which attributed to increase in soil temperature induces decline in persistence. Benitez et al. (2006) also reported that increased water temperature increase the photodegradation rate of several phenyl-urea pesticides. However, recently in India a number of studies on pesticide persistence under elevated CO_2 have been carried out. Table 8.2 summarizes the elevated CO_2-induced changes on degradation of half-life of some pesticides studied under subtropical soils of India. Kumar et al. (2017) reported faster dissipation of tricyclazole under increased CO_2 condition as compared to ambient CO_2. Khandelwal et al. (2014) have also reported that elevation of CO_2 level from 385 to 550 ppm slightly increases the degradation of fungicide kresoxim-methyl. Faster degradation of pretilachlor and butachlor under elevated CO_2 condition has also been reported by Mukherjee et al. (2018). Chatterjee

Table 8.2 Persistence of some pesticides under elevated CO_2

Pesticides	Half-life in soil (days)				References
	Unchambered control, i.e., open field	Chambered control	Elevated CO_2 concentration (ppm)		
Chlorpyrifos	2.4	1.8	1.7 (550)	1.7 (700)	Adak et al. (2016)
Pretilachlor	–	14.7–28.5(398)[a]	10.7–23.7(450)	7.1–18.2(550)	Mukherjee et al. (2018)
Butachlor	–	26.3–59.4(398)	19.4–52.2(450)	11.8–44.5(550)	Mukherjee et al. (2018)
Flubendiamide	177–181.1	168.4–172.3(398)	159.3–155.3(570)	–	Mukherjee et al. (2018)
Tricyclazole	–	167.2 (385)	144.7 (550)	125.4(750)	Kumar et al. (2017)
Kresoxim-methyl	–	6.4(375)	3.9(550)	–	Khandelwal et al. (2014)
Metaflumizone	–	33.4–50.1(375)	21.5–30.1(550)	20.1–27.3(750)	Chatterjee et al. (2013)
Azoxystrobin	20.3	19.3(~390)	17.5 (580)	–	Manna et al. (2013)

[a] Data in parenthesis indicate the CO_2 concentration in ppm

et al. (2013) found that degradation of metaflumizone was the highest at 550 ppm level of CO_2, followed by 750 ppm level and ambient condition and faster degradation in Oxisol compared to Inceptisols. However, degradation of pesticide chlorpyrifos under elevated CO_2 was not due to elevated CO_2 but due to the increased temperature in elevated CO_2 chambers compared to unchambered control as reposted by Adak et al. (2016). Manna et al. (2013) also found that elevated CO_2 induced nonsignificant decrement in degradation half-life of azoxystrobin in rice-planted soil. However, these short-term studies may not be representing the actual field level information. Since global warming is continuous and cumulative process, more studies have to carry out on long-term basis in order to determine realistic assessment on impacts of global warming on pesticide degradation.

8.3.2 Increased Temperature and Pesticide Degradation

Along with the changes in atmospheric CO_2, global temperatures are also predicted to change, and it is expected that the direct and indirect influence of temperature on fate of xenobiotics like pesticides is very relevant. Though ample studies on changing temperatures are available, the phenomenon is still not well-understood. As per the predication of IPCC, there will be a further increase in global average of temperature by 1.1–6.4 °C (IPCC 2007). Furthermore, along with this increase in the average temperature, extreme high temperature frequency will also increase (IPCC 2012).

As Earth has warmed (IPCC 2007), considerable reports are available about the variation of soil temperature in different parts of the world, such as China (Wang et al. 2014; Sofi et al. 2018), Turkey (Yeşilırmak 2014), Canada (Qian et al. 2011), Alaska and Siberia (Oelke and Zhang 2004), and Russia (Zhang et al. 2001). As 99% of sprayed pesticides will reach to the soil, increase in soil temperature has some possible influences on pesticide degradation rates. It is a well-known fact that between 10 and 45 °C temperature, with an increase of every 10 °C temperature, the reactions rate catalyzed by enzymes will be doubled. So, increment in soil temperature will stimulate the rate of pesticide degradation. High temperature-induced enhancement of pesticide degradation has been reported by Mukherjee et al. (2016) for flubendiamide, Watters et al. (1983) for synthetic pyrethroids, and Kaur et al. (1998) for endosulfan. Temperature also alters the mineralogy and geochemistry of soil (Woodruff et al. 2009) and thus influences the pesticide leaching (Bloomfield et al. 2006; Yadav et al. 2017b).

Elevated temperature in the atmosphere increases the volatilization of pesticides which leads to faster degradation (Bloomfield et al. 2006; Otieno et al. 2013; Varma et al. 2017b). Both biotic and abiotic factors involved in pesticide degradation are influenced by temperature and thus enhance or slow down the rates of degradation reactions and change the active degradation channels in the environment (Getzin 1981). Reports are available where warmer weather leads to higher rate of volatilization of organochlorine pesticides (Nations and Hallberg 1992; Yeo et al. 2003). Pesticides like dieldrin, heptachlor epoxide, and gamma-HCH have been re-emitted from previously contaminated soil or snow surfaces due to high temperature as reported by Bossi et al. 2008.

Changes in climate variables like temperature and precipitation (Nolan et al. 2008; Lewan et al. 2009) influence pesticide fate directly where one can counteract another one. For instance, increased temperatures or increased soil moisture contents will enhance the pesticidal degradation rates, whereas leaching is increased by higher rainfall (Bloomfield et al. 2006; Beulke et al. 2004;.). Not only the pesticides fate but ecotoxicity of pesticides is also influenced by temperature. Reports are available for proportional relation of temperature and pesticide toxicity (Noyes et al. 2009; Seeland et al. 2012). However, pyrethroids and DDT shows more toxicity under low temperature environment (Noyes et al. 2009). The temperature-induced changes in ecotoxicity of pesticide may be due to alteration of toxicokinetic profile as a consequence of degree of difference in absorption, distribution, and elimination (Seeland et al. 2012; Gogoi et al. 2018). Several studies (Delorenzo et al. 2009; Greco et al. 2011; Seeland et al. 2012; Mitran et al. 2018) have reported high temperatures induced enhancement of acute toxicity of applied pesticides on *Chironomus riparius*, *Palaemonetes pugio*, and *Mya arenaria*. However, the effect of pesticide-temperature interaction on *Physella acuta* is life-stage specific. Study also showed that the average mortality of *Daphnia magna* was increased due to cumulative effect of exposure of fungicide and temperature stress (Seeland et al. 2012; Yadav et al. 2017a). Finally identifying and understanding the actual mechanism of effect of temperature on pesticide toxicity will be more realistic in calculating the actual risk assessment of pesticides under global warming situation.

8.3.3 Role of Salinity on Pesticide Degradation

Due to anthropogenic reasons, the global climate change is being accelerated and consequently led to many ecosystems' alterations. Warmer temperatures and sea ice melting are important contributing factors that led to sea level rise, which is causing saltwater intrusion into many ecotones. It has been predicted that by the last of this century, there would be a significant decline in freshwater resources due to sea level rise (SLR) of 1.8–5.9 mm year^{-1} and anticipated global temperature increase of 1.1–6.4 °C. Climate change can also induce intense tidal surges and intrusion of saltwater into groundwater, and thus salinization of coastal freshwater ecosystems, conversion of agricultural land, salt mining, and runoff of road deicers are the other contributing factors which led to freshwater salinization (Denoël et al. 2010; Corsi et al. 2010; Chun et al. 2018). This will lead to chemical pollutant-induced toxicity to estuarine and marine organisms (Jiao et al. 2015) as fate, bioavailability, and toxicity of pollutants are influenced by water salinity (Heugens et al. 2001; Moore et al. 2003; Waring and Moore 2004; Schiedek et al. 2007; Fortin et al. 2008; Varma et al. 2017a). Due to "salting out" effect, solubility of the neutral pesticides will be reduced as a result of preferential solvation of ionic compounds, like salt ions by water molecules at the expense of neutral compounds. On the other hand, salinity will enhance the solubility of polar pesticides. This differential solubility will lead to the bioavailability of neutral pesticides and thus their toxicity particularly in subtropical latitudes which are experiencing increased salinity. Brecken-Folse et al. (1994) reported that under increased salinity, sheepshead minnow *(Cyprinodon variegatus)* and grass shrimp *(Palaemonetes* spp.) experienced a decreased toxicity by methyl-parathion metabolite 4-nitrophenol. However, salinity increases the acephate toxicity to the mummichog *(Fundulus heteroclitus)* (Fulton 1989). Due to salinity-induced enhanced activity of flavin-containing monooxygenases (FMO), the toxicity of aldicarb to the Japanese medaka *(Oryzias latipes)* (El-Alfy and Schlenk 1998), juvenile rainbow trout (*Oncorhynchus mykiss*), and striped bass (*Morone saxatilis* x chrysops) (Wang et al. 2001) has been reported. Song and Brown (1998) reported that due to salinity-induced higher accumulation and bioavailability of organophosphate pesticide, dimethoate increases the toxicity toward salt marsh mosquitoes (*Aedes taeniorhynchus*) and brine shrimp (*Artemia* sp.). They also reported that due to salting out effects, persistence of organophosphate pesticide, malathion, is higher in seawater (half-life 3–5 days) than in freshwater (half-life 1 day). High doses of the atrazine (>2.6 mg l^{-1}) increases the mortality of estuarine copepods (*Eurytemora affinis*) under both high (25 ppt) and low (5 ppt) salinity levels (Hall et al. 1995). Further research would be necessary to investigate the salinity impact on environmental fate of pesticides under multiple environmental parameters like organic matter, suspended sediment, water pH, temperature, and turbulence which can affect the fate of pesticides.

8.4 Climate Change Associating with Leaching of Pesticides

Under influences of climate change, global agriculture is likely to face challenges to secure food for all. The crop-pest interaction will alter due to change in micro- and macroclimate and all favoring pests compared to crops (Miraglia et al. 2009; Noyes et al. 2009; Jackson et al. 2011; Roos et al. 2011; Yadav et al. 2017c). Climate change is expected to affect the agricultural production more in developing countries as compared to the developed countries. Therefore, pesticide application is likely to be more in developing countries; even the banned/restricted use pesticides may be reintroduced (Macdonald et al. 2005). Hence, use of pesticides will be increased due to climate change.

Pesticides are used to control the targeted pests. Figure 8.2 represents a schematic diagram of fate of pesticide after application. Only 10–30% of the total applied pesticides reach the target site, and majority of pesticides (nearly 70–90%) reach nontargeted sites. While applying pesticides directly as dust/spray, drift loss is an important issue. Climate change projections indicated a probable change in wind circulation (by 10–20%), and hence, it will affect the drift loss during pesticide application. However, farmers can take necessary preventive action by checking desired wind condition for spray/dusting. Climate change is expected to increase frequency of storms and floods, which will directly affect pesticide losses through runoff. Runoff containing pesticides (5–15%) may reach surface water bodies and contaminate them (Ficklin et al. 2010; Otieno et al. 2013; Kumar et al. 2018b). Increase in precipitation under the influence of climate change will result in washing loss, and frequent application will

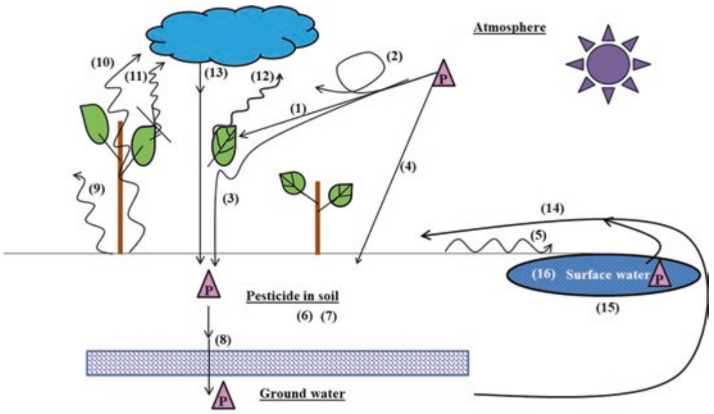

Fig. 8.2 Environmental fate of pesticide (P) after application: (1) direct application on plant as dust/spray, (2) drift loss, (3) nontarget pathway to soil, (4) direct soil application/soil fumigation, (5) runoff and erosion loss, (6) pesticide sorption in soil, (7) degradation (chemical/microbial) of pesticide, (8) pesticide leaching, (9) soil photodegradation loss, (10) volatilization of pesticide from soil, (11) volatilization of pesticide from leaf surface, (12) photodegradation on leaf surface, (13) condensation and precipitation of volatilized pesticides with raindrops, (14) crop irrigation with pesticide containing groundwater/surface water, (15) accumulation in sediments, (16) bioaccumulation

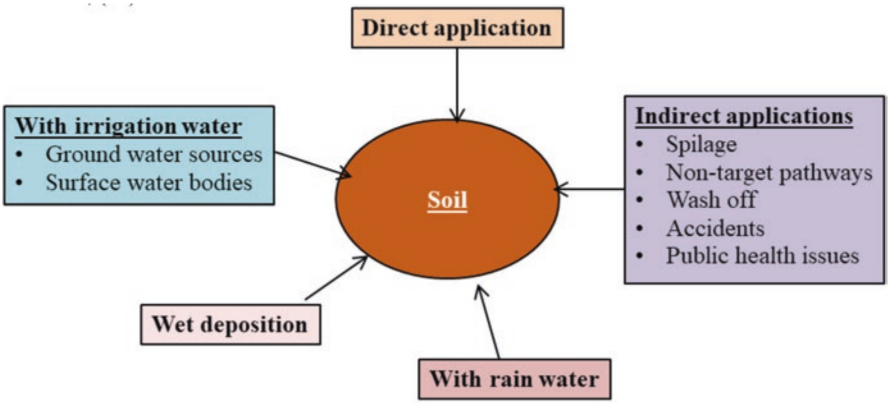

Fig. 8.3 Probable pathways for pesticides reaching soil

be required for pest control. A large portion of pesticides reach soil, as direct and indirect applications (Fig. 8.3). Soil acts as a sink for receiving pesticides, and several interactions occur in soil environment. Pesticides present on the soil surface may undergo volatilization and photodegradation. Similarly, photo-transformation/photodegradation and volatilization of pesticides also occur on foliage surface (Yeo et al. 2003; Layek et al. 2018). Reports have indicated that volatilization is directly proportional to the soil temperature and moisture. Studies reported that volatilization of pesticides will be more under the scenario of climate change due to increase in temperature, sunlight, and precipitation levels (Otieno et al. 2013). The volatilized pesticides/transformed compounds can disperse with wind to a new area and may get deposited on the new land as aerial inputs or along with precipitation (Bloomfield et al. 2006; Donald et al. 2007). Soil also receives pesticides while irrigating water is contaminated with pesticides. In the soil, the fate of pesticide is governed by three major processes like sorption, degradation, and leaching. Sorption is the most important process which determines the availability of pesticide in soil for further interactions like degradation and leaching. Climate change, which predicts warmer climate, will inversely affect the pesticide adsorption onto soil, and hence, soil available pesticide concentration will increase. At higher temperature, water solubility of pesticides increases, which results in lower sorption tendency onto the soils (Chiou 2002; Kong et al. 2008; Rani and Sud 2015). Further, increased temperature may alter characters/functionalities of soil humus which influences pesticide sorption (Broznic et al. 2012; Meena and Lal 2018). Low sorption results in the availability of pesticide in soil which is prone to degradation and/or leaching. Studies indicated that pesticide degradation will be accelerated under the scenario of climate change (Wang et al. 2009; Kookana et al. 2010; Buragohain et al. 2017), with contradictory case of 2,4-D degradation in alkaline soil (Shymko et al. 2011). After sorption and degradation, the most important process is pesticide leaching. It's a downward transport of pesticide through different soil profiles, before reaching the groundwater. Soil properties, climatic conditions, and property of pesticide play very important roles in pesticide leaching. Table 8.3 shows the effect of temperature and precipitation on leaching of pesticide (Bloomfield et al. 2006; Loewy et al. 2006; Woodruff et al. 2009). The groundwater ubiquity score (GUS) is frequently applied to rate leaching potential of pesticides. The

Table 8.3 Effect of climatic changes on leaching

Climatic parameter	Interactions in soil	Effect on leaching	Probable cause
↑ Temperature	↓ Sorption	↑ Leaching	Adsorption ↓, desorption ↑ and water solubility ↑, resulting in higher soil available pesticide for leaching
	↑ Volatilization	↓ Leaching	Reduces total pesticide load on soil
	↑ Degradation	↑Leaching of transformed products	Chemical/microbial degradation often results in polar transformed/degraded products which are leachable. In case microbial degradation, the reaction rate doubles for each 10 °C increase of temperature between 10 and 45 °C
↑ Precipitation	↓Sorption	↑ Leaching	Higher precipitation will result in decrease in sorption by reducing the time of contact and by increasing the water solubility, hence higher leaching
	↓ Volatilization	↑ Leaching	Pesticides do not get sufficient time to volatilize

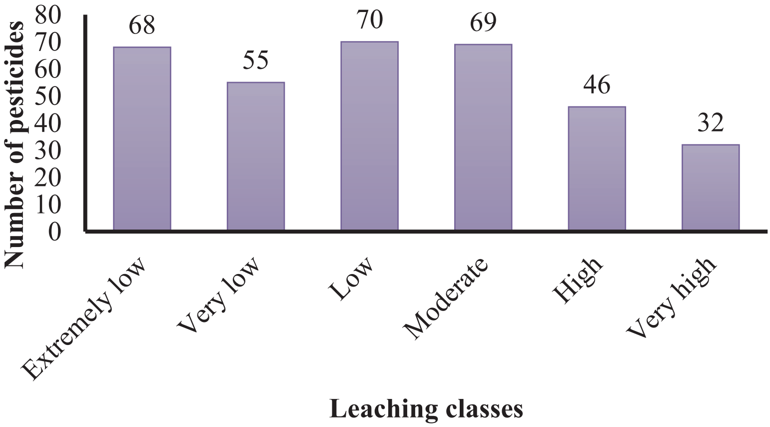

Fig. 8.4 GUS leaching classification of 340 pesticides

GUS is calculated from the persistence ($t_{1/2}$, half-life) of pesticide and sorption (K_{oc}) in soil. Based on this GUS values, pesticides can be classified as extremely low (GUS ≤ 0.1), very low (GUS = 0.1–1), low (GUS = 1–2), moderate (GUS = 2–3), high (GUS = 3–4), and very high (GUS ≥4) leacher. Figure 8.4 presents different leaching classes of pesticides as per GUS (Augustijn-Beckers et al. 1994). More than 50% pesticides are very low to moderate leacher. Only 23% pesticides are prone to high to very high leaching.

8.5 Bioavailability and Toxicity of Pesticides as Affected by Climate Change

Contamination of open water bodies and groundwater with pesticides is a known fact (Werner et al. 2004; Moschet et al. 2014). The main cause of such contamination is direct applications and indirect routs. Indirect roots contribute maximum to such kind of contamination by means of runoff, wash off, spillage loss, and drainage from farm lands and urban areas, public health applications, and accidental spills (Weston and Lydy 2012). When pesticide is present in water, it becomes an easy passage to invade the food chain by contaminating the lowest trophic level and reaching to the highest trophic level via the process of bioaccumulation and biomagnification. The concentration of pesticides is generally high in rain/drainage water immediately after pesticide application, and thus, huge quantities of pesticides go to surface water bodies with these rain/drainage water. Climate change will increase frequency of storms, rains, and floods, and it is likely to increase the pesticide loads in water bodies. Once the pesticide enters the aquatic system, the ecotoxicity will be determined by physical properties of water, structural properties of pesticide molecule, and physiology of each aquatic species. The interactions between the pesticide (dissolved and particulate) and aquatic organism are very complex. The log K_{ow} (octanol-water partition coefficient) is commonly applied as an indicator of bioaccumulation potential. As per European Union (2009), pesticides with log $K_{ow} \geq 3$ have bioaccumulation potential. Hence, bioaccumulation and toxicity data are required for these types of pesticides before registration and marketing. The toxicity of pesticides to aquatic organisms is a complex interplay of several factors (Table 8.4). Not only the properties of the dissolved pesticides but presence of suspended particles, specifically the organic carbon attached to the particle, significantly influences the fate and bioavailability of pesticides in aquatic environments. The pH of water influences the degree of ionization of pesticides and surface property of the adsorbing matter, which in turn controls pesticide sorption, and subsequently availability of pesticide to the aquatic organisms. The physiological behavior like feeding nature and digestive capacity of aquatic organisms affect the degree of bioaccumulation of pesticide and also the pesticide toxicity. Under the influence of climate change, occurrence of hot waves and heat extremes will increase along with a rise in the mean temperature. These changes are likely to alter the water temperature which may induce physiological stress in aquatic organisms (Greco et al. 2011; Verma et al. 2015c). A positive correlation between temperature rise and ecotoxicity has been observed (Delorenzo et al. 2009; Seeland et al. 2012; Ram and Meena 2014), however, with exceptional inverse relation for pyrethroids and DDT (Noyes et al. 2009). Temperature rise may alter the metabolism, pesticide uptake, and toxicokinetic profile resulting higher toxicity of pesticides (Table 8.5).

Table 8.4 Pesticide bio-toxicity under influence of climate change

Climate change projections	Changes in aqueous phase	Pesticide status	Pesticide toxicity	Physiological condition of aquatic organism
Mean average temperature ↑ in the tune of 1.1–6.4 °C	↑ Temperature	Change concentration	↑ (except DDT and pyrethroids)	Species, growth stage, habits, size, metabolism
Ocean acidity ↑ in the tune of 0.14–0.35 pH units due to increase in CO_2 concentration	↑ Acidity	Change in log(K_{OW}) and log(K_{OC})	↑	Ionization of pesticide and alteration of pesticide uptake rate, metabolic behavior
Change in sea level and ocean circulation	↑ Salinity	Change in molecular structure, ↓ solubility, salting out effect	↑ (except lindane, chlordane, endrin, DDT)	Digestive pattern of organism

Table 8.5 Effect of change in temperature and salinity on pesticide toxicity

Organism	Pesticide	Change in toxicity with increasing temperature	Change in toxicity with increasing salinity	References
Algae				
Dunaliella tertiolecta	Irgarol, diuron, atrazine, and ametryn	↑	↑	Delorenzo et al. (2009)
Macrophyte				
Stuckenia pectinata	Atrazine	-	↑	Hall et al. (1995)
Mollusks				
Mya arenaria	2,4-D, dicamba, mecoprop	↑	-	Greco et al. 2011
Crustaceans				
Microarthridion littorale	DDT	-	↓	Staton et al. (2002)
Callinectes sapidus	DDT	↓	–	Koenig et al. (1976)
Chironomus dilutus	DDT, pyrethroids	↓	–	Harwood et al. (2009)
	Chlorpyrifos	↑	–	
Aedes taeniorhynchus and *Artemia* sp.	Dimethoate, aldicarb, tebufenozide	–	↑	Song and Brown (1998)
Palaemonetes spp.	Terbufos, trichlorfon	↑	↑	Breken-Folse et al. (1994)
	4-Nitrophenol	↓	↓	
Palaemonetes pugio	Resmethrin	↓	–	DeLorenzo et al. (2009)
	Chlorothalonil	↑	↑	
	Permethrin	–	↑	
Fish				
Cyprinodon variegatus	Terbufos, trichlorfon	↑	↑	Breken-Folse et al. (1994)
	4-Nitrophenol	↓	↓	
Oncorhynchus kisutch, Oncorhynchus tshawytscha, Salmo gairdneri, Gasterosteus aculeatus	Guthion, malathion, CoRal, aldrin, dieldrin, DDT, methoxychlor, toxaphene	–	↑	Katz (1961)
	Endrin, chlordane, lindane	–	↓	

8.6 Chemical and Biological Properties of Pesticide-Contaminated Soils as Affected by Climate Change

Soil chemical and biological properties are the most important parameters to be considered for soil health management and sustainable agriculture production. Pesticides are the necessary evil for intensive agricultural production system. Pesticides are essential for meeting the global food security, but their adverse effect cannot be ignored particularly when environment-friendly agriculture is the universal focus. It is well known and widely discussed about the adverse effect of pesticides on environment and human health; they are also responsible for influencing soil chemical and biological properties. Soil biological properties (microbial biomass carbon, basal respiration, enzyme activities) represent soil microbial status and have been considered as bioindicators of soil health (Avidano et al. 2005). Due to long persistence of pesticide residues in soil, their adverse effect on soil microflora is obvious (Prashar and Shah 2016). A range of soil functions and properties like pH, soil organic carbon, rhizodeposition, bulk, and rhizospheric soil is strongly influenced by pesticides application. All these parameters are responsible for soil microbial population dynamics which directly and indirectly influence pesticide degradation and residual toxicity (Nannipieri et al. 1990). Due to climate change (CO_2 concentration and temperature), the fate of pesticide residue may be influenced due to change in soil microbial population (Manna et al. 2013). However, there is a possibility of complex response as fate of pesticide residue (Bloomfield et al. 2006; Manna et al. 2013; Mukherjee et al. 2016) and soil microbial activities (Drigo et al. 2008; Li et al. 2010; Das et al. 2011) are directly influenced by climate change. There are a good number of studies that described the effect of climate change on fate of pesticide residue and soil chemical and biological properties separately. However, comparatively less information is available on climate change-induced soil biological properties of pesticide-contaminated soil (Manna et al. 2013). The impact of climate change particularly the increase in CO_2 concentration and temperature on biological activity of pesticide-contaminated soil has been presented in Table 8.6. The available information suggested that elevated CO_2 led to increase in temperature which resulted in decrease in pesticide persistence (Williams et al. 1992; Bailey 2003). Most of the studies indicated increase in microbial biomass carbon (MBC) and enzymatic activity in pesticide-treated soil under elevated CO_2 and temperature (Manna et al. 2013; Chatterjee et al. 2013; Khandelwal et al. 2014; Adak et al. 2016; Mukherjee et al. 2016; Dadhich et al. 2015). Simultaneously, it was also observed that faster dissipation reduces persistence of pesticides in soil under elevated CO_2 and temperature. The reduced persistence of pesticides in soil might be due to higher degradation rate at elevated CO_2 and temperature. Soil microbial parameters may also accelerate the degradation of pesticides (Adak et al. 2016). Significant correlation between phosphatase enzyme activity and organophosphate pesticide degradation in soil was also reported (Sikora et al. 1990). Manna et al. (2013) reported elevated CO_2 did not change enzyme activity in azoxystrobin-treated soil, whereas Adak et al. (2016) reported enzyme activity in chlorpyrifos-treated soil responded positively to elevated CO_2 concentration.

Table 8.6 Effect of climate change on soil biological properties of pesticide-contaminated soil

Pesticides	Climate change parameters	Impact on soil biological properties	References
Azoxystrobin	Elevated CO_2	Increased soil microbial biomass carbon (MBC) but did not increase azoxystrobin degradation	Manna et al. (2013)
Metaflumizone	Elevated CO_2 and temperature	Higher MBC observed in oxisol with faster degradation of the pesticide under elevated CO_2 and temperature	Chatterjee et al. (2013)
Kresoxim-methyl	Elevated CO_2	Higher microbial population and faster dissipation of kresoxim-methyl under elevated CO_2 concentration	Khandelwal et al. (2014)
Chlorpyrifos	Elevated CO_2	Irrespective level of CO_2, short-term negative influence of chlorpyrifos was observed on soil microbial activities	Adak et al. (2016)
Flubendiamide	Elevated CO_2 and temperature	Decrease in persistence of flubendiamide and increase in MBC in soil	Mukherjee et al. (2016)

8.7 Role of Soil Amendments in Mitigating the Impacts of Climate Change on Pesticides Fate

A soil amendment is any material which upon addition to soil improves the physical properties, usually its fertility, and sometimes its functions. It is mostly used to improve structure, organic matter content, fertility, and biological activities of soil. But it has an important role as a corrective material for remediation of problem soils. Bioaugmentation of soil amended with organics can significantly change biogeochemistry and subsequently influence pesticide degradation, retention, and dissipation. Recently, there is an increasing interest regarding consequences of organic matter application on the pesticide fate in soils (Blackshaw et al. 2005), because retention and degradation properties of pesticides in soil matrix determine its environmental behavior (Worrall et al. 2001). So, application of organic amendments may have significant role in influencing the environment fate of pesticides. The effects of different soil amendments on the fate of pesticides are presented in Table 8.7. Application of organic amendments (manures and composts) increase pesticide degradation (Moorman et al. 2001; Dungan et al. 2003; Getenga 2003; Castillo et al. 2016) in soil due to rapid improvement in microbial activity. Sometimes the organic amendments increase the pesticide retention in soil through sorption and reduce the possibility of leaching to groundwater (Sluszny et al. 1999; Cox et al. 2001; Said-Pullicino et al. 2004; Joshi et al. 2016; Kumar et al. 2017). Biochar is important soil amendments which increase pesticide retention through adsorption (Zhelezova et al. 2017; Dhakal et al. 2016), reduce the negative impact of pesticides on microbial community of soil (Ahirwar et al. 2018), and also mitigate climate change effect. Some of the inorganic amendments like zeolite, diatomaceous earth, and calcined clays were found effective in increasing retention of pesticides in soil through physical capture and adsorption (Wehtje et al. 2000). As a

Table 8.7 Effect of soil amendments on fate of pesticides in mitigating climate change

Pesticides	Soil amendments	Effect on fate of pesticides	References
Triazine, Atrazine	Cattle manure	Increase degradation	Moorman et al. (2001)
Methyl isothiocyanate	Chicken manure	Increase degradation	Dungan et al. (2003)
Triazine, Atrazine	Compost	Increase degradation	Getenga (2003)
Thiocarbamate triallate	Animal manures (pig slurry)	Increase retention and reduce leaching to groundwater	Senesi et al. (2001)
Triazine, Simazine	Sewage sludge	Increase retention and reduce leaching to groundwater	Cox et al. (2001)
Fipronil	Fresh cow dung	Increase retention	Joshi et al. (2016)
Atrazine	Composted sewage sludge	Increase retention and reduce leaching to groundwater	Sluszny et al. (1999)
Triasulfuron	Municipal waste compost	Increase retention and reduce leaching to groundwater	Said-Pullicino et al. (2004)
Diuron	Biochar	Increase adsorption	Zhelezova et al. (2017)
Diuron	Vermicompost	Increase degradation	Castillo et al. (2016)
Chlorpyrifos	Biochar	Nullify the negative effect on soil microbial community	Ahirwar et al. (2018)
Imazaquin, oxadiazon, fenarimol	Zeolite, diatomaceous earth, calcined clays	Increase retention	Wehtje et al. (2000)

consequence of climate change, i.e., elevated CO_2 and temperature, there is a possibility of higher mineralization of organic amendments, leading to significant consequences on beneficial effect of the amendments.

8.8 Modeling on Climate Change-Induced Impacts on the Fate and Behavior of Pesticides

The fate of pesticides under the scenario of influence of climate change is of most significance to the policy makers as pesticide fate will change with the changing nature of temperature and precipitation. Under climate change, the change in arable land use pattern will result in cultivation of new crops, changed time of application (e.g., frequent application in autumn crops), or application of different pesticides against newly emerged pests (Whitehead et al. 2009). However, the climate change will have a positive correlation on dose and frequency of pesticide application. Hence, the environmental load of pesticide is expected to increase under changed climatic conditions. Therefore, understanding the fate of pesticide under climate change has become very important. Fate and transport of pesticides in soil depends on interaction of various physical, chemical, and biological factors. Mathematical models provide an easy and quick method for estimating various losses which are tedious to estimate under real field conditions. Further models provide the opportunity of assessing various management practices. Pesticides present in soil are transported with water in dissolved state and as erosion of pesticide adsorbed soil particles. Models for transport and fate of pesticides consider two major processes, namely, hydrology and chemical processes (Dubus et al. 2002; Siimes and Kamari 2003; Datta et al. 2017b). The hydrology processes involve certain parameters like flow of water (Armstrong et al. 2000), evapotranspiration, drainage (Skaggs 1978), surface runoff (Mocus 1972; Ma et al. 1999), erosion (Renard et al. 1997), preferential pathways (Elliott et al. 2000), and winter hydrology (Flerchinger et al. 2000; Verma et al. 2015b) covering snow accumulation, soil frosting, snow melting, etc., whereas the chemical processes involve sorption (Brucher and Bergstrom 1997; Craven 2000), degradation (Vanclooster et al. 2000), transport (Klein 1995), and effect of plant on pesticide. There are various mathematical models available; however, selection of a model is a very important process. The models have been reported mostly from developed counties like Britain, Sweden, the Netherlands, the USA, etc. Though several models have been reported, few have been thoroughly used by several researches to evaluate the fate and transport of pesticides. The commonly used models are the following:

1. Groundwater Loading Effects of Agricultural Management Systems (GLEAMS); origin: Georgia, USA
2. Pesticide Root Zone Model (PRZM); origin: Georgia, USA
3. Leaching Estimation and Chemistry Model (LEACHM); origin: NY, USA
4. CRACK-NP, a British model for cracking clay soils; origin: Great Britain
5. Erosion-Productivity Impact Calculator (EPIC); origin: Texas, USA
6. MACRO: Pesticide fate in macroporous soils; origin: Sweden
7. OPUS: Fate of nonpoint pollutants in field; origin: Colorado, USA
8. Pesticide Leaching Model (PELMO); origin: Germany
9. Pesticide Emission Assessment at Regional and Local scales (PEARL); origin: the Netherlands
10. Pesticide Leaching and Accumulation (PESTLA); origin: the Netherlands
11. Pesticide Leaching Model (PLM); origin: Great Britain
12. Root Zone Water Quality Model (RZWQM); origin: Colorado, USA
13. SIMULAT; origin: Germany

Table 8.8 represents comparative evaluation of commonly used mathematical models. It shows hydrological and chemical feathers of various models. There is limited guideline for selection of a model. Uncertainty is an important issue which is missing in most of the models. Uncertainty may come from data used in model and/or from model itself. Dubus et al. (2002) described several reasons for uncertainty in pesticide fate modeling. Fate and transport of pesticide in soil is an

Table 8.8 Overview of hydrological and chemical feathers of various models

	Hydrology processes							Chemical processes								
Model	H-1	H-2	H-3	H-4	H-5	H-6	H-7	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8	C-9
GLEAMS	√ (C)	√ (S)	√	√ (1)	X	X	√	√	√	√ (E)	√ (L)	√ (OC)	√ (1)	SM, ST, SD	√	√ (C)
EPIC	√ (C)	√ (S)	√	√ (1)	X	X	√	√		√ (E)	√ (L)	√ (S)	√ (1)	X	X	√ (C)
PELMO	√ (C)	√ (S)	√	√ (1/2)	√	X	√	√	√	√ (E + N)	√ (F)	√ (OC/ pH)	√ (1)	SM, ST, SD	√	√ (C)
PLM	√ (C)	X	X	X	√	√	X	X	X	√ (E + N)	√ (L)	√ (I)	√ (1)	SM, ST, SD	X	√ (C)
PRZM3	√ (C/R)	√ (S)	√	√ (2/3)	X	X	√	√	√	√ (E)	√ (L)	√ (S)	√ (2/3)	ST	√	√ (C)
CRACK-NP	√ (C)	√	X	√ (2)	√	√	X	X	X	√ (E)	√ (L/F)	√ (I)	√ (1)	SM, ST	X	√ (C)
LEACHM	√ (R)	X	X	√ (2)	X	X	X	X	√	√ (E + N)	√ (L/F)	√ (I)	√ (1)	SM, ST, SD	X	√ (C + d)
MACRO	√ (R)	√	X	√ (2/4)	√	√	√	√	√	√ (E)	√ (F)	√ (I)	√ (4)	SM, ST, SD	√	√ (C + d)
OPUS	√ (R)	√	√	√ (6)	√	X	√	√	√	√ (E + N)	√ (L)	√ (OC)	√ (1)	SM, ST, SD	X	√ (C + d)
PEARL	√ (R)	√	X	√ (2/4)	√	X	X	√	√	√ (E + N)	√ (F)	√ (OC/ pH)	√ (1)	SM, ST, SD	√	√ (C + d)
PESTLA	√ (R)	√	X	√ (2/4)	√	X	X	X	√	√ (E + N)	√ (F)	√ (OC)	√ (1)	SM, ST, SD	√	√ (C + d)
RZWQM	√ (R)	√	X	√ (5)	√	√	√	√	√	√ (E + N)	√ (F/L)	√ (OC/ pH)	√ (5)	SM, ST, SD	√	√ (C + d)
SIMULAT	√ (R)	X	X	√ (4)	√	√	X	X	X	√(E + N)	√ (F/L/ La)	√ (S)	√ (1/3/6)	SM, ST, SD	√	√ (C + d)

H-1 = Water flow: C, capacity model; R, Richard’s model
H-2 = Surface runoff: S, SCS curve number method
H-3 = Erosion
H-4 = Evapotranspiration: 1, 2 calculation options; 2, as input; 3, Hamon’s equation; 4, Penman-Monteith equation; 5, modified Penman-Monteith equation; 6, Ritchie’s equation
H-5 = Drainage
H-6 = Preferential flow
H-7 = Winter hydrology
C-1 = Plant foliar application
C-2 = Plant uptake
C-3 = Sorption dynamics: E, equilibrium sorption; N, non-equilibrium sorption
C-4 = Sorption Isotherm: L, linear isotherm; F, Freundlich isotherm; La, Langmuir isotherm
C-5 = Sorption in deeper soil layers: OC, sorption parameters calculation from Koc and % organic carbon content of soil layers; S, same sorption parameters used for all layers in whole simulation profile; I, separate sorption parameters are given for each soil horizon
C-6 = Degradation kinetics: 1: 1st order kinetics,2: separate 1storder kinetics in two phases, 3: metabolic & co-metabolic degradation, 4: separate 1st order kinetics in four phases,5: pseudo 1st order kinetics; 6, Michaelis-Menten kinetics
C-7 = Degradation affecting factors: SM, soil moisture; ST, soil temperature; SD, soil depth
C-8 = Degradation metabolites
C-9 = Transport equation: C, convection; d, dispersion and diffusion

interplay of various physical, chemical, and biological factors. Hence, if few of these factors/processes are wrongly/incompletely implemented or ignored, these will create uncertainty in the models. Use of improper model will result in wrong simulation of data, leading toward unrealistic and impractical conclusions. Policy/decision-makers can make regulatory decisions confidently if a model is providing robust results with defined uncertainties (Costanza et al. 1992).

8.9 Future Prospective

Other than altering the distribution and toxicity of pesticides, climate change will also alter the structural and functional properties of many ecosystems. So, for correct estimation of impact of pesticides under warming world, it is necessary to conduct mesocosm experiments which are more environmentally relevant in determining the nontarget effects. Moreover, emphasis should be given toward multi-stressor studies where climate changing parameters combined with other anthropogenic stressors.

Under climate change, factors linking pesticides fate and behavior may vary between the field scale and larger scales. Along with the direct effects, how climate change indirectly impacts on pesticide behavior needs to be considered as without that the predictions cannot be significantly affected, and thus chances of drawing false conclusions will be increased. In order to reduce the risk of drawing false conclusions, policies have to be adopted related to relevant mitigation practices and management strategies. Strict implementation of mitigation strategies will definitely protect our current and future environment and health from adverse effect of pesticides as influenced by the climate change parameters.

Methodical analysis of historic data on fate and behavior of pesticide, their use pattern with time-series climate data will enable us about the confident assessment on impacts of climate change on pesticides degradation and transport in future. Moreover, catchment-based modeling studies on fate and behavior of pesticide under the climate change will be more relevant to give any future insights about the pesticides fate.

8.10 Conclusion

In conclusion, climate change impacts on pesticide fate and behavior are closely associated with consumption and use pattern of pesticides, rises in temperature, variations in global water cycle, cropping pattern, type of crop cover, absorption and metabolism of pesticides, degradation pathways, and many more multiple interacting complex processes. To address these complex processes, contribution and understanding of multidisciplinary science from different branches includes climate science, agricultural science, toxicology and environmental modeling, exposure and public health, social science, and chemical ecology, and a range of other sectors through the world is required. A time-series observational data on long-term basis with large-scale research projects throughout the globe with interdisciplinary science is also needed. Detection of banned pesticides in environmental media under changing scenario suspects its re-emission, though there is a gradual decrease of primary source that indicates the urgency of the study of contribution of climate warming on secondary emission.

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9

Agricultural Socio-economic Effects in Colombia due to Degradation of Soils

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Abstract

Colombia, due to its tropical context of adverse climatic regimenes intensified by global climatic change, join to geological complex and geomorphologic linked to Andean System of Mountain Range and a vast alluvial plain, which are soils highly susceptible to degradation by erosion process, landslides, salinization, in the soil sustainability and Agricola useful are impacted.

Through different studies the indicators of soil degradation in Colombia show a profressive increase. From the continental extension, 114.2 million hectares, nearly 48% of Colombian land, have shown some degradation level, with 14.2% being high affectation, 8.9% moderate, 9.5% low, and 4.6% very low degradation intensity.

The agriculture sector in Colombia shows a reduction in the growth rate, from 3.0% to 1.8% during the 2002–2016 period, and then the gross domestic product is placed below of growth rates. This phenomenon is due to soil degradation, which affects abandoned areas abandoned and occupation to other places, growing border agriculture area, pushing over strategic ecosystems.

This chapter contribution sets out some goals such as to open spaces for proposal generation that join to mitigating politic measures for soil erosion and to look for agriculture sustainable management strategies and make an effort in the way to avoid dietary safety issues.

Keywords
Soil degradation · Colombia · Agriculture · Dietary safety competitiveness

Abbreviations

AGRONET	Information and communication network of the agricultural sector
ANH	National Hydrocarbons Agency
ANM	National Mining Agency
APU	Agricultural production unit
CEPAL	Economic Commission for Latin America and the Caribbean
CONPES	The National Council for Economic and Social Policy
DANE	National Administrative Department Statistics
DNP	National Planning Department
ENA	National agricultural survey
GDP	Gross domestic product
IDEA	Institute of Environmental Studies
IDEAM	Institute of Hydrology, Meteorology and Environmental Studies
IGAC	Geographic Institute Agustin Codazzi

INDEPAZ	Institute for Development and Peace
INDERENA	National Institute of Renewable Natural Resources and Environment
MADS	Ministry of Environment and Sustainable Development
MPI	Multidimensional poverty indicator
OECD	Organisation for Economic Co-operation and Development
PSE	Producer support estimate
UMPE	Mining energy planning unit
UNDP	United Nations Development Programme
UPRA	Rural agricultural planning unit

9.1 Introduction

The relationship of humans with the earth is essential since their life depends on it because it is the source of their food, physical and cultural and symbolic. The loss of soil despite not being a new phenomenon, in recent years, has gained global relevance, affecting a large number of people in different sectors of the planet. Its causes are multiple and its effects are related to the loss of food security, the reduction of competitiveness, and the erosion of cultural diversity.

The loss of land in a certain region of the world is the product of a network of multiple factors, including those related to development models and macroeconomic and sectoral policies that privilege one sector to the detriment of others. The derivatives of the forms of appropriation and structure of land tenure, and those that are the product of natural processes, should also be considered. In Colombia, these causes are associated at the same time with deforestation, the expansion of the agricultural frontier generated by illicit crops, the intensification of agricultural activities, and the changes in use caused by mining and urbanization.

The purpose of this chapter is to show the state of the degradation of soils and soil in Colombia by natural and anthropic processes, together with their impacts or socioeconomic effects. To do this, we begin with the characterization and current state of soils in the morphological regions of the country. Second, the cadastral analysis is used to identify the land tenure structure that has typified the country in recent decades, influencing the different economic and human activities that are implemented in them. These processes have led to conflicts over changes in land use, displacement of populations in search of new spaces for production and human settlements, and dynamics that in turn affect not only the loss of soil quality but also the loss of quality of life of the populations and the sustainability of the territories.

The methodology that guided this work was supported by recent research processes, in which the authors of this chapter participated. Likewise, reference was made to the primary information obtained from the fieldwork carried out in the regions worked and analysis of remote sensing images and official cartography of the soil situation in Colombia. The cadastral information obtained from the IGAC became a fundamental instrument for the processing and understanding of the forms of land tenure in Colombia. The population census, the agrarian census, the national food survey, and the economic statistics were processed, worked on, and incorporated into the respective analyses. Of great importance are the sources such as the development plans, the sectoral plans, the policy for the sustainable management of the soil, and some documents of the academy, especially those of the National University of Colombia, a product of the research carried out in soils and ecosystems strategic among others.

Another topic developed in this section refers to the role of public policy, especially macroeconomic, sectoral, and territorial policy, in the evolution of soils in Colombia and its effects on the economic dynamics in the territory. Therefore, the development models that have been directed toward the country in recent years have devoted an important space to the extractivist model related to natural resources, thus putting emphasis on the displacement of economic activities, mainly producers of food and raw materials, putting at risk the areas that can guarantee territorial sustainability.

In this socioeconomic context, an institutional budget is required that considers reference knowledge and other logics of reordering of the territories that allow the economic growth with development, based on the knowledge and the management of the territory that recognizes the current state of the soils, its most suitable potentialities, and more appropriate uses that are economically and environmentally viable.

9.2 Natural Context of the Colombian Territory

Colombia is divided naturally into five major regions as a result of its geographical, climatic, physiographic, geological, and pedological characteristics. It boasts the Caribbean, Andean Pacific, Orinoquia, and Amazon regions, ensuring that across the country a great diversity of soils and uses are to be found (IGAC 1995) (Fig. 9.1).

9.2.1 The Caribbean Region

The Caribbean region is located in the northern part of Colombia, where its boundaries to the east and north are formed by the Caribbean Sea. Its continental zone covers an approximate area of 11.1 million hectares, representing 10% of the country's continental surface. The region is characterized by large geomorphological provinces: La Guajira, Sierra Nevada de Santa Marta, Serrania de Perijá, and the foothills of the Central and Western Cordilleras and the insular region, with islands, cays, and marine banks, the highlights of which include the islands of San Andrés and Providencia and the cays de Roncador, Serrana, and Quitasueño. The climate is characterized by a decreasing humidity toward the north-east. In the region of Urabá and the foothills of the Central and Western Cordilleras, precipitation values are above 2.000 mm/year and the climate is thus classified as very humid, with desaturated acid soils. In the central zone, the climate is humid. Rainfall is of the order of 1.000 mm' year^{-1}. Finally, there is the strip of tropical dry climate that goes from

Fig. 9.1 Map of the natural regions of Colombia

the Cesar River valley to the Guajira Peninsula, where saturated basic soils are found, often with excess salts.

Geologically, igneous, sedimentary, and metamorphic rocks are found, their ages ranging from the Quaternary to the Proterozoic. Unconsolidated Quaternary deposits cover these rocks discordantly and are alluvial, eolic, colluvial, and marine coastal sediments. The igneous and metamorphic crystalline rocks are found mainly in the mountain areas such as Sierra Nevada de Santa Marta, Serrania de Perijá, Serranía de Macuira, Serranía de Jarara, and the foothills of the Eastern and Central Cordilleras. The sedimentary rocks are detrital and calcareous.

From the point of view of soil taxonomy at the order level, the Caribbean region has aridisols, entisols, inceptisols, mollisols, alfisols, and histosols. Aridisols occur in the area of the upper Guajira, due to its arid climate, with a very low degree of evolution and salic horizons. As regards the physiography, alluvial plains, lake environments, coastal plains, mountain soils, and windblown desert soils are characteristic (IGAC 1995).

Soils of alluvial and lacustrine origin are associated mainly to the lower basins of the Magdalena and Cauca rivers. In general, they are poorly drained and subject to the periodic action of floods due to frequent overflows. In zones of a transitional humid/dry climate, in a characteristic landscape of savanna, there are superficial to moderately deep soils very poor in nutrients for plants, with hardened horizons and concretions of iron (IGAC 1995).

Piedmont or fan soils form a plain through the action of the surrounding rivers, in an inclined relief with slopes of 7–12% dominant. The soils located in the warm, dry climate are evolved, deep to moderately deep, well drained, and generally saturated, on the whole, suitable for commercial agriculture, such as in the banana zone between Ciénaga and Fundación. There are also, in the savanna landscape, semiarid and eroded soils with salts and sodium. These limit agricultural use.

The soils of the littoral, or coastal, plain are located in relatively narrow areas along the coasts. They are of marine and/or lacustrine origin. On these plains, areas of mangrove and sandbars are found. The parental materials change from coral beds, organic deposits, and brackish materials. Sandy, poorly drained soils predominate and are not well evolved and with high salt content. In general, their use is restricted to the growth of natural vegetation such as mangroves.

In the hill soils, dry climatic conditions predominate, affected by moderate to severe erosion. They are generally well drained, with high saturations of bases, with a pH close to neutral. They are dedicated to extensive livestock farming or are covered with natural vegetation of no great use. There are small areas in subsistence agriculture and in crops such as tobacco, sweet potato, cassava, maize, and plantain.

The area of La Guajira, in the northernmost part of Colombia, represents the country's arid and semiarid zones. Situated at altitudes of less than 100 m above sea level, it covers an area of about 2% of the national territory. Climate is the most important factor in the genesis of the La Guajira soils. The climate is characterized by rainfall of less than 300 mm year^{-1}, poorly distributed. As a result, the peninsula is known for its variation from dry forest to spiny forest. The lack of precipitation, high temperatures, excessive water loss by evaporation, strong winds, and direct incidence of solar energy have contributed to the formation of soils whose most outstanding characteristics are the marked deficiency of usable humidity for plants, the abundance of carbonates, the tendency to compaction of soil materials, the intense erosion that often decapitates the soil profile, the presence of layers of sand transported by the wind, the poverty in organic matter, and the basic pH across most of the territory. Despite the common properties mentioned, the mosaic of the soils is varied and contrasting, such as alluvium and colluvium, windblown soils, glacial soils or erosion surfaces, and lastly those evolved from the Guajira plain. With the exception of the colluvial/alluvial plains that are generally suitable for extensive cattle ranching and crops typical of the region, the soils offer no agricultural possibilities (Fig. 9.2).

The alluvial and colluvio-alluvial soils in this region are from areas of the plains that are not exposed to flooding, located on high terraces with well-drained drainage channels. The soils are generally deep and varied in texture with a high saturation of bases. Heterogeneous, saline, and compacted materials constitute the soils of the foothills that border these mountainous areas (Vargas 2007).

Fig. 9.2 Examples of soils and morphology of Alta Guajira in the Caribbean region

Littoral soils are poorly drained and located in various relief forms typically covered with mangrove vegetation. Beaches with no soil formation, sandbanks, and sandbars with poorly drained, sandy soils or high salt content are also typical.

The soils of the wind plain are formed on sandy surfaces of varying natures. These are poorly evolved soils with very little pedogenetic development. They have a sandy texture, low fertility, excessive drainage, and a considerable thickness (<150 m), and in some sectors, they are affected by salts and sodium. The soils from the hill and mountain range areas of the Guajira, such as Cosinas, Jarara, Macuira, and Perijá, are extremely shallow and stony.

9.2.2 The Andean Region

The Andean region is formed by mountains of the South American Andes range, which on entering Colombia in the Colombian massif divides into three parallel ranges, or *cordillera*, called Eastern, Central, and Western. The first two are separated by the inter-Andean valley of the Magdalena River and the Central and Western by the Cauca River valley. This region covers an approximate area of 32.9 million hectares, representing 29% of the national territory. Given the great variety of factors that affect the development of the soils of this region—such as climate, parent materials, relief and differences in altitudinal floors—the Andean region presents a great diversity of lithological materials and soils.

From a geological point of view, the region is characterized by the presence of all types of igneous, sedimentary, and metamorphic rocks with ages from Precambrian to Quaternary. These rocks have notable tectonic effects due to faulting and folding associated with their orogenic processes. The action of the rain on these rocky materials exerts a high action in the various processes of weathering, decomposition and alteration, with the development of thick residual soils susceptible to erosive processes, and of mass removal (Fig. 9.3).

The Eastern range contains predominantly sedimentary and crystalline rocks associated with massif, mountain range, igneous and metamorphic mountains such as the Colombian Massif to the south, the Garzón massif in the central-southern part, the Floresta massif, the Quetame massif, and the Santander massif. The materials of the Central range are mainly igneous and metamorphic crystalline rocks. The Antioquia batholith is composed of granite rocks, the Ibague batholith of granite and volcanic igneous rocks, and the Cajamarca group mainly of metamorphic rocks. Important volcanic deposits that characterize the central region of the Colombian Andes, due to the predominance of pyroclastic volcanic ash and agglomerate materials, constitute the area known as the Coffee Belt. The materials of the Western range meanwhile, by their island arc origin, are mainly volcanic, Cretaceous and Tertiary basaltic lavas. Due to slope dynamics in the Andean region, the

Fig. 9.3 Examples of fractured and folded rock materials and unconsolidated deposits in the Andean region

predominant unconsolidated deposits are the colluvial materials and, in the inter-mountain valleys, fluvial-torrential deposits.

Up in the cordilleras themselves, a variety of soils are found, ranging from those rich in organic matter in the high, cold parts to the eroded and poor soils in humus from lower altitudes. Soils are present in all types of textural families, from the clayey to the sandy extreme; in the steeply sloping rocky areas, the soils are not well evolved, while in the low areas of gentle topography, there are soils with more pedogenetic development. In the dry regions of any floor and in calcareous materials, the soils are highly saturated. In humid climates, they are washed and poor with low base saturation. From a taxonomic point of view, the soils of the Andean region are variable and with a wide variety. Soil types recorded (IGAC 1995) include entisols and inceptisols in the Eastern and Western ranges; vertisols, mollisols, and alfisols in the alluvial valleys of Cauca and Magdalena; and andisols in the Central range and the Colombian massif.

The inter-Andean valleys are valleys of the Cauca and Magdalena rivers. The first runs between the Central and Western and the second between Eastern and Central Cordillera. The Cauca Valley is a region of great importance due to the quality of its soils and its climate characteristics. With the exception of some of the soils located in the extreme south of the valley in humid conditions, the area features high base contents, high base saturation, and medium to high cation exchange capacity, with a basic or close to neutral pH and with a good level of fertility. The soils also tend, however, to have phosphorus deficiencies, and some sectors show salt and sodium problems. Nevertheless, one of the properties for which the soils of the Cauca Valley are famed is the great variety of technically exploited crops typical of the region, including sugarcane, sorghum, bean, soybean, cotton, rice, tomato, vine, cassava, fruit trees, and pastures.

The Magdalena Valley is located on the warm thermal floor, since it ranges from altitudes of 400 m to the south of Huila to 25 m near La Gloria, Cesar. There are very marked differences in conditions of humidity. Notable within this context are a subhumid province in the upper part of the basin, a semiarid province at the heights of Baraya, a humid province between Puerto Berrio and Barranca, and a transition toward a dry climate in the final part of the middle valley. The soil properties and climate characteristics enable varied agricultural use. Huge areas classified as the most productive in the country feature cash crops such as rice, cotton, sesame, soybean, peanut, sorghum, and corn and, on a smaller scale, fruit trees, cassava, and plantain; in the middle Magdalena, important herds have been established that indicate the suitability for such use. Likewise, the success of crops such as African palm in Santander and Cesar stands out.

9.2.3 The Pacific Region

The Pacific region is located on the western side of Colombia, bordered by the Pacific Ocean from the northwestern border with Panama to the border with Ecuador in the southwest. Physiographically, it includes the Pacific plain, Serranía del Baudó, the Atrato depression, and the foothills of the Western Cordillera. It covers an approximate extension of 7.6 million hectares, representing 7% of the national territory. It is one of the wettest regions of the country, given that in some areas, there are rainfall records of more than 8000 mm year^{-1}. This ensures the classification of these areas, according to Holdridge, as a humid and very humid tropical rain forest. It is wholly located within the warm thermal floor, with temperatures higher than 25 °C and heights above sea level of less than 400 m.

The Pacific region, due to its climatic and coastal characteristics, is composed mainly of sediments of littoral and alluvial piedmont origin that partially and discordantly cover sedimentary and igneous volcanic rocks. Crystalline massifs, such as the Baudó and Darién mountains to the north, are composed of igneous and metamorphic crystalline rocks. The unconsolidated deposits are associated with extensive alluvial and littoral plains of marine terraces and intertidal plains of clay composition. Deposits of black sands of volcanic origin predominate in the coastal zone with the formation of extensive beaches by intertidal processes (Fig. 9.4).

Marine soils are poorly drained or with high contents of salts. Some are also formed with organic deposits with different degrees of decomposition. Alluvial soils are composed of fine and moderately coarse sediments with poor drainage conditions; these also remain flooded in a large part of the area, which is why they present very little pedogenetic development. Hill soils are desaturated, with a very acid pH, moderately to badly drained, and of very low fertility. The soils of these

Fig. 9.4 Examples of lithological materials from the Pacific region

mountain ranges are poorly evolved, very superficial and severely affected by erosive processes. Taxonomically, Pacific region soils are mainly entisols, inceptisols, and histosols.

9.2.4 The Orinoquia Region

The Colombian Orinoquia region is located in the eastern part of Colombia and is commonly known as the Eastern Plains. It covers an approximate area of 21.7 million hectares, corresponding to approximately 19% of the area of the country. Physiographically, it includes the altillanura, or high plains, the mountainous area of La Macarena and the hills of the Guayana Shield in its easternmost part. The climate shows rainfall greater than 3.500 mm in the foothills and this progressively decreases to 1.700 mm in the Arauca plains. The average temperature is above 25 °C. The dominant vegetation in most of the area is constituted by different types of tropical savanna in 70% of the Colombian Orinoquia, associated with gallery forest in the margins of influence of the waterways and rivers.

Geologically, the Orinoquía is characterized by a predominance of sedimentary Tertiary and Quaternary formations that make up the altillanura. Toward the eastern side, on the banks of the Orinoco River, the igneous rocks of the Guayana Shield from the Precambrian age appear, composed mainly of granites that form hills and rocky plains. This high plain feature important ferruginous concentrations of different forms and origins related to the mineralogy of the parent granitic material, arid paleoclimates, morphology, and pedogenetic processes among others that characterize the reddish soils of the region. These concentrations of iron are manifested in the form of crusts or sheaths in the inclined planes (pediments) located around the granite domes, nodular crusts or sheaths, alveolar crusts or sheaths, and crusts or sheaths from alluvial accumulation. Unconsolidated Quaternary deposits that discordantly cover sedimentary Tertiary and Precambrian igneous rocks are composed mainly of alluvial deposits in the beds of the Meta and Bita rivers, wind deposits of transverse dunes of past activity and lacustrine deposits since the area is frequently flooded. (Fig. 9.5).

In most of the soils of the Orinoquía, there are no organic horizons and non-decomposed organic matter is very scarce. The soils have a very low level of fertility, as the poverty of organic matter and nutrients for plants shows, along with a marked acidity and the presence of aluminum in toxic amounts. Taxonomically, the soils are spodosols (associated with Guayana Shield materials and of low fertility, high acidity, and low exchange capacity), ultisols and oxisols.

9.2.5 The Amazon Region

The Colombian Amazon is located in the southeastern part of Colombia and is part of the large Amazon basin. It covers a total area of 40 million hectares, representing 35% of the continental surface of Colombia. It includes heights above sea level

Fig. 9.5 Lithological materials from the Orinoquía region

between 0 and 800 m, with a tropical, rainy climate with rainfall between 2.500 and 3.500 mm year^{-1} and temperatures above 25 °C.

Geologically, Amazonian residual soils predominate in the region, the product of decomposition of sandy and clayey sedimentary rocks from the Tertiary. In the Amazon, sedimentary massifs rise above the stretches of jungle, formed by sandstone and quartzite with a crystalline base of igneous and metamorphic Precambrian composition from the Amazonian and Guayana Shield. Outstanding among these mountain ranges are the Serrania de Chiribiquete, the Serranía de La Lindosa, and the Serranía Naquén.

The soils of the jungle plains are poorly drained and periodically flooded. They are fine in texture with low fertility. The hill soils are well drained, moderately superficial, very acidic, and of low fertility, while the soils associated with the Guayana Shield are very low fertility, sandy-clayey in texture, poorly drained, and rich in iron and aluminum. Taxonomically, the soils in the Amazon are classified as entisols, inceptisols, spodosols, ultisols and oxisols (IGAC 1995) (Fig. 9.6).

Fig. 9.6 Lithological materials in mountainous areas of the Amazon region. Sandstones in the Tiuna river, Serrania de Chiribiquete; granites in Cerro Mavacure, Puerto Inírida; quartzites in the Serrania de Chiribiquete; sandstones and shales in the Serranía de la Lindosa

9.3 Soil and Land Degradation Processes in Colombia

Owing to its tropical nature, Colombia can be considered as a green country because of the high-water availability that promotes good soil development and high vegetation coverage. Despite this, the contrasting morphology, high weathering of rocky materials, and their high degree of fracturing and deformation due to folding give rise to degradation processes of soils and lands of different types, among which the most prevalent and that affect crops are erosion, mass movements, hydromorphism, and salinization. Climatic, biotic and pedological effects produce zones in desertification.

9.3.1 Erosion and Mass Movements

Physical degradation processes include erosion and mass movements. Erosion can be defined in different ways, although the general concept is related to any natural agent that is capable of detaching and transporting terrestrial material. Three types of erosion were identified from the cartography of processes: concentrated water erosion (rills, gullies, and ravines), sheet erosion, and wind erosion. The mass movements known as landslides include several types such as falls, flows, slumps,

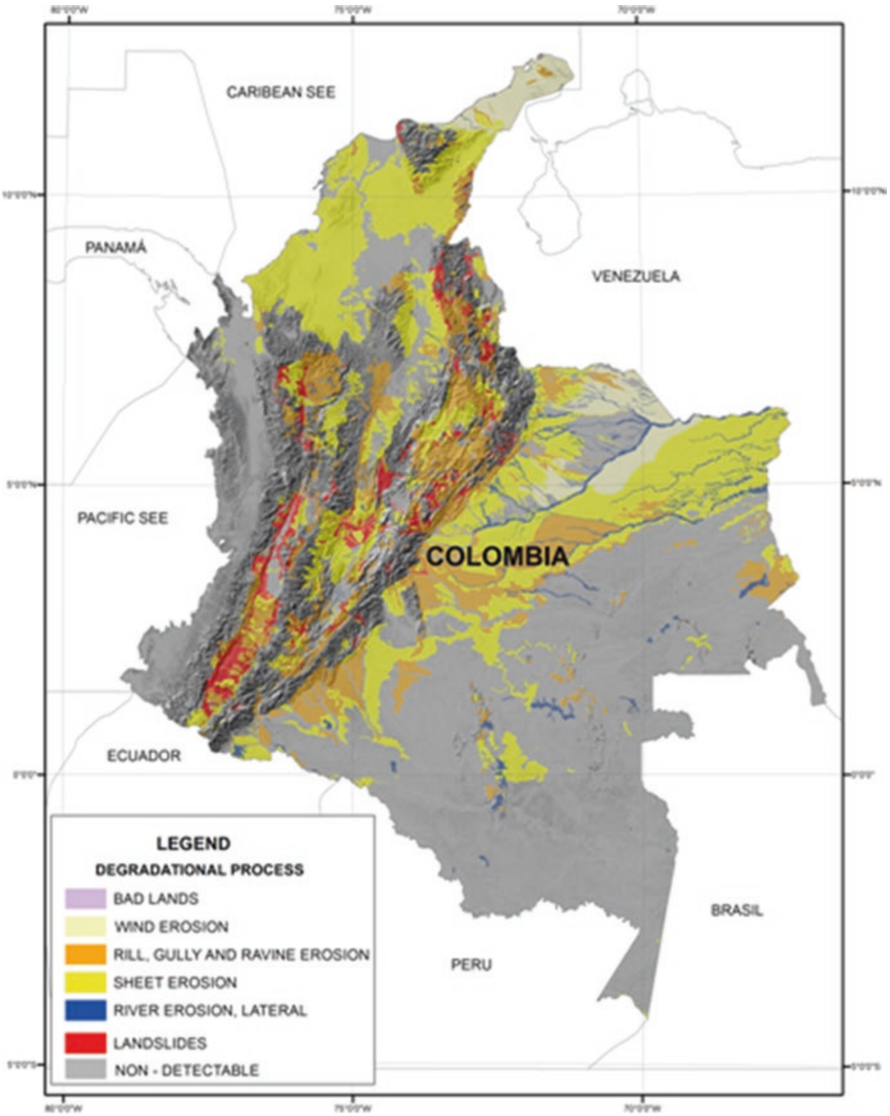


Fig. 9.7 Map of natural processes of erosion and mass movements

toppling, lateral propagation, subsidence, creeping, complex movements, torrential streams, and avalanches. (Fig. 9.7).

The erosive processes of water erosion due to diffuse laminar runoff cover an approximate area of 240.547 km^2 in Colombia, occurring mainly in the alluvial plains of the Caribbean, the high plain of Orinoquía, the Magdalena valley and in the highlands of the mountain ranges. Hydric erosion concentrated in channels such as rills, gullies, and ravines cover a total area of 130.000 km^2 and occurs discontinuously and dispersed in the Andean region, the mountains and some hills of Orinoquia and the Amazon mountains such as Chiribiquete. The processes of fluvial erosion by lateral undermining are present in the large rivers, particularly the rivers of the Piedmont llanero and in the eastern plains of the Orinoquia and Amazonia, such as the Meta and Guaviare rivers. Wind water erosion due to the action of the wind occurs particularly in northern Colombia, in the Alta Guajira area, and in eastern Colombia in the Arauca and Vichada areas. Processes of complex erosion (badlands) cover a total area of 263.5 km^2 and occur in the basins of the Chicamocha, Cauca, and Mondoñedo (highlands of the Sabana de Bogotá) rivers, Villa de Leyva, Tatacoa, etc. (Fig. 9.8).

The mountain ranges of the Colombian Andes feature a large number and type of movements in mass. Among the most predominant are falls, flows, landslides, toppling, and torrential streams. Areas of high concentration of these movements occur in the high basin of the Cauca River, in the basin of the Chicamocha River, in the basin of the Blanco River, upper basin of the Magdalena River, Colombian Massif, Serrania de Perijá, and Motilones, Sierra Nevada de Santa Marta, Serrania de los Cobardes, etc. These processes cover a total area of 26.844 km^2. Creeping processes due to deforestation on steep slopes affect agricultural areas in the Colombian

Fig. 9.8 Erosion processes. Badlands in Mondoñedo, Cundinamarca; sheet erosion in Villa de Leyva, Boyacá; water and wind erosion in Los Estoraques, in Bucaramanga's plateau, Santander

Fig. 9.9 Examples of mass movements in the Colombian Andes. Creeping, Bogotá-Villavicencio road; landslide, Bogotá-Villavicencio road; landslides in Paz del Río, Boyacá and landslide in Cocuy, Boyacá

Andes and torrential flood processes are common in foothill areas forming fluvio-torrential fans. (Figs. 9.7 and 9.9).

9.3.2 Hydromorphism

Hydromorphism, or waterlogging, occurs when the soil of aerobic conditions is submerged under water or frequently flooded and the oxygen in the pore space is insufficient for plant roots to be able to breathe.

Water saturation in the soil expels oxygen from the soil. The absence of this element results in the rapid disappearance of aerobic organisms so that decomposition of organic matter is carried out under anaerobic conditions, leaving accumulations of carbonic gas, organic acids, and other compounds, of which the first two present the greatest toxicity problem to plants. When the metabolism is aerobic, CO_2 acts as an electron receptor and therefore favors oxidation conditions, but in anaerobic environments, processes of soil reduction predominate and these processes cause drastic physical and chemical changes, most notably a lowering of the oxidation-reduction potential, and changes in ph. In acidic or alkaline soils after several weeks of flooding, pH values stabilize at close to 7.0, with an increase in electrical conductivity, and chemical changes. Among the most important chemical changes that occur in flooded soils are loss of nitrogen due to denitrification, accumulation of ammonia compounds in the soil, and an increase in the concentration of iron and manganese in the soil solution.

A common physical characteristic that varies with the changes that occur in the soil are the changes of colors according to the action of the levels of water. In the zones of alternation determined by the movement of water, that is, zones of wetting and drying, the oxidized forms of iron and manganese prevail and for this reason horizons appear with mottles of irregular colorations with red, brown, and yellow; while in the areas that remain saturated with water, the dominant colors are gray and blue characteristics of reduced compounds. Due to these characteristics, zones, where hydromorphism processes occur, are associated with soils of orders such as entisols, histosols, and inceptisols.

In Colombia, these areas occur in the alluvial plains, plains, savannas, littorals and alluvial high plains, and marine plains in the upper Guajira, the floodplain of the Canal del Dique, the floodplain of the Lower Magdalena and Lower Cauca, coastal plains of Urabá and the Pacific, the floodplain of Bajo Sinú, in the foothills of the northern and southern plains, the Orinoquia altillanura through its major channels of the Arauca, Meta, Bita, and Guaviare rivers, among others, and the savannas of the Colombian Amazon in the beds of its tributaries such as the Amazon, Vaupés,

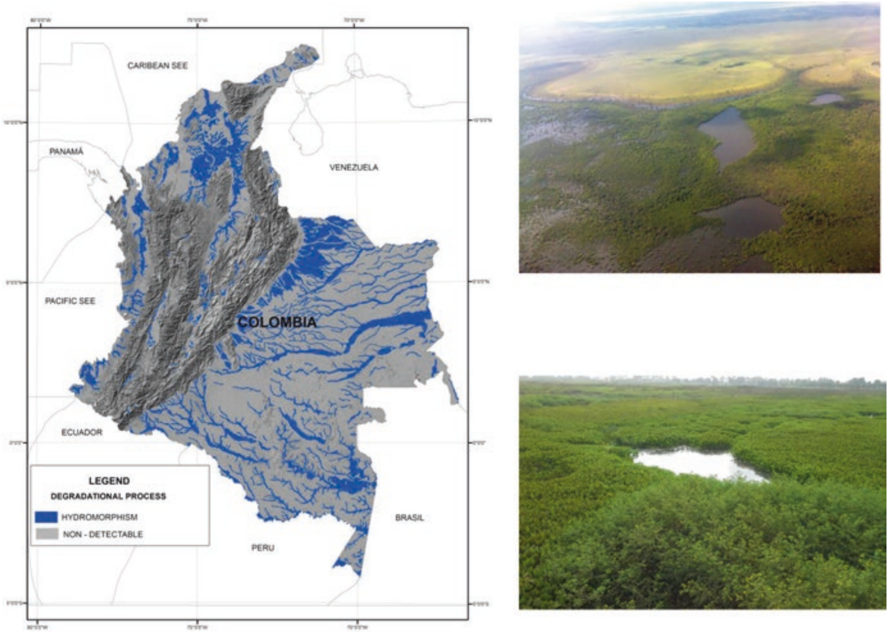


Fig. 9.10 On the left, map of hydromorphic processes in Colombia; in the upper right part floods in the high plain; and in the lower right, part hydromorphic zones in the floodplain of the Canal del Dique

Caquetá, Apaporis, and Putumayo rivers. These areas cover a total area of 216.433 km^2 (Fig. 9.10).

9.3.3 Mining

Anthropic activities cannot be considered as processes of soil erosion, but as constraints in agricultural processes because they restrict their use in many cases. These activities include mining, urban planning, and civil works. Legal mining activity in Colombia is regulated by the State, in accordance with the current Political Constitution. In this legislation, the mining industry is declared of public utility and social interest, an important factor when supposing itself to be above the territorial ordering in the country. Colombia, through its geology and orogenic, tectonic, and volcanic processes, can be considered as country rich in mineral resources including gold, silver, nickel, emeralds, and coal, among others, whose concessions for which are granted to private companies through mining titles by the National Mining Agency (ANM, from the Spanish acronym). These titles, which number close to 9000, cover approximately 4.6 million hectares. Conflicts between the use of land for agricultural, livestock, and other activities and use of the subsoil through mining activities have been raised by Herrera (2016), with great legal, social, economic,

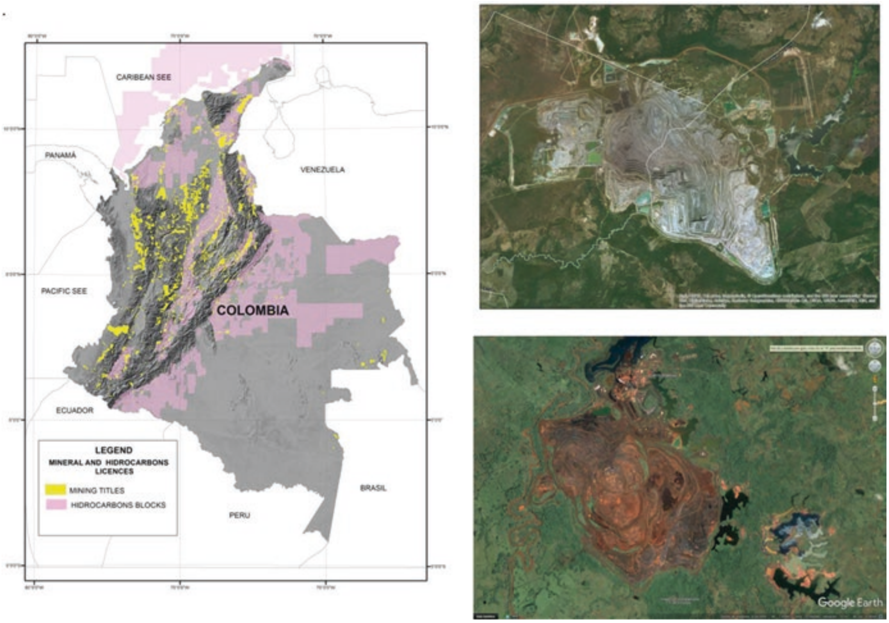


Fig. 9.11 On the left, a map of mining titles and blocks of oil exploration and/or exploitation in Colombia; in the upper right, image of the Cerrejón coal mine; and in the lower right the nickel mine in Cerromatoso, Montelibano. (Sources: ANM (2016); images Esri-Base Map and Google Earth)

and environmental effects. Colombia is also a country with hydrocarbon resources (gas and oil), important for domestic supply and export. As of 2016, there were 502 block concessions for exploration and/or exploitation, adding up to a total area of 40.5 million hectares (Fig. 9.11).

9.3.4 Intensity of Soil Degradation by Erosion

The intensity of degradation is generally determined by the quantification of the loss of soils associated with one or several types of processes such as erosion or mass removal. With this objective, several methodologies have been proposed as the index of intensity of sheet erosion at detailed scales (MOPT 1992) (Table 9.1).

For concentrated water erosion, Van Zuidam (1985), proposes indices for the measurement of the intensity by the geometry and density of the channels in rills, gullies, and ravines (Table 9.2).

The Universal Soil Loss Equation of Wischmeier and Smith (1978) comes from numerous previous experiences and formulations such as the Zingg (1940), who related erosion to the degree of slope and length of hillside, Musgrave (1947), who added a climate factor based on maximum rainfall in 30 min with a return period of 2 s, and Wischmeier and Smith (1958), in which crop factors that took into account the different degree of soil protection provided by the vegetation cover were considered.

Wischmeier Erosivity

$$\boxed{A = R * K * LS * C * P}$$

Table 9.1 Index of intensity of sheet erosion at detailed scales (MOPT 1992)

Erosion intensity	Description
Low	Removal and drag of 25% of arable surface layer (less than 5 cm)
Moderate	Removal and drag of 25–75% of the topsoil (5–15 cm)
High	Removal and drag of more than 75% of the topsoil and part of the subsoil (more than 15 cm)
Very high	Removal and drag of most of the soil profile

Table 9.2 Indexes of erosion intensity by erosion in channels at detailed scales (Van Zuidam 1985)

A. RILLS	B. GULLIES	C. RAVINES				
Type and depth	Spacing (m)					
	5	5–15	15–50	50–150	150–500	>500
A. <50 cm	Severe	Moderate	Low			
B. 50–150 cm	Severe	Severe	Moderate	Low		
150–500 cm	Severe	Severe	Severe	Moderate	Low	
> 500 cm	Severe	Severe	Severe	Severe	Moderate	Low

R = Annual Erosivity Index (Ton-m/ha.hr)

E = Kinetic energy (Ton-m/ha.cm)

I = Maximum intensity in 30 min (cm h^{-1})

Wischmeier does not take into account precipitations of less than 1.27 cm, considering that they did not contribute to any considerable increase in the R index. He also considers as independent rainfalls those separated by an interval of 6 h.

Other numerical methods for determining the degradation of soils and lands have been put forward by Lal (1990) and Salvati and Zitti (2008). Other methods based on GIS technologies and remote sensing are presented in the work of Chandramohan and Dilip (2002), Pandey et al. (2009), Krishna (2009), Prasannakumar et al. (2011), Devatha et al. (2015) and Ganasri and Ramesh (2016).

In Colombia, the results of several studies show, using different methods, the intensity of soil and land degradation. Notable among these are INDERENA (1977), IGAC (1988), IGAC (1998), IDEAM (2000), IGAC (2004) and IDEAM et al. (2015) (Table 9.3 and Fig. 9.12).

According to the last study on the state of soil degradation in Colombia (IDEAM et al. 2015; Ashoka et al. 2017; Sofi et al. 2018), the areas with the highest erosion rate are found in the Caribbean region, particularly the upper Guajira, as well as in the Andean region in the upper watersheds of the Magdalena and Cauca rivers, and in the Chicamocha river basin. In the region of the Orinoquía, processes of erosion of light to moderate intensity appear. The Pacific and Amazon regions present more local processes with moderate to light intensity.

9.3.5 Crops and Pastures in Colombia

Cultivated areas in Colombia, according to land cover mapping (Corine Land Cover), from 2012 at 1:100.000 scale, prepared by UNAL-IDEAM (2012), cover a total area of 14.343.237 hectares. Of these, nearly 2 million hectares are found in the Caribbean area, with 14.4%; 9.1 million hectares in the Andean region, with 64.3%; 1.1 million hectares in the Orinoquía region, with 8.3%; 982.808 hectares in the Pacific region, with 6.8%; and 858.056.9 hectares in the Amazon region, with 6% of total crops for that study period (Fig. 9.13).

The predominant crops in the Caribbean region are palm oil, transient crops with pastures, fruit tree crops, conifers, rice and coffee in some sectors of the Sierra Nevada de Santa Marta. The Andean region is the most diversified in crops, given its thermal floors. Coffee crops predominate, along with small transient crops such as peas, beans, corn, fruit trees, cotton, cocoa, sugarcane, cereals, vegetables, bananas, palm oil, tubers, etc.

In the Orinoquia region, crops are concentrated predominantly in the foothills of the plains with a variety of transient crops, forest plantations, herbaceous crops, palm oil, and rice. In the Amazon, crops predominate in the foothill zone of the Eastern Cordillera and correspond to areas of transitory crops, with pastures and natural spaces. Pastures, which are devoted mainly to livestock activities according to the map of UNAL and IDEAM (2012), cover a total area of 15.4 million hectares,

Table 9.3 Relation of statistics of soil and land degradation in Colombia by different studies

Study	Methodology and scale	Degradation processes	Intensity of degradation (%)	
INDERENA (1977)	Compilation of studies, generalization of homogeneous zones, Scale 1: 1′000,000	Water erosion Wind erosion Mass removal	No erosion Water erosion Mass removal Wind Erosion	24.8 51.4 23.5 0.3
IGAC (1988)	Reference information, remote sensing interpretation of some areas, scale 1: 3′400.00	Water Erosion Wind erosion Mass removal Alkalization Acidification Toxicity Biological degradation	No erosion, other areas Very light Light Moderate Severe Very severe	48.53 1.98 4.96 23.11 12.9 7.9 0.73
IGAC (1998)	Visual interpretation of Landsat satellite images, scale 1: 500,000	Erosion Sedimentation Rocky outcrops	No erosion, other areas Not appreciable Light Moderate Severe Very severe Wind Sedimentation Outcrops	14.7 44.9 19.5 11.3 3.3 0.5 1.0 2.0 1.2
IDEAM (2000)	Processing and digital interpretation of Landsat TM images, 1990s 1: 100,000	Water erosion Wind erosion, Anthropogenic Mass removal Sedimentation	Without degradation Very low Low Moderate High Very high	52 4.6 9.5 8.9 10.8 14.2
IGAC (2004)	Visual interpretation of Landsat images between 1993 and 1997	Water erosion Wind erosion, Sedimentation	No erosion, other areas Not appreciable Light Moderate Severe Very severe Sedimentation and wind Outcrops	14.63 44.83 19.51 11.33 3.3 0.54 1.04 1.24
IDEAM, MADS and UDCA (2015)	Study prepared following the protocol for the identification and evaluation of soil degradation by erosion IDEAM, MADS and UDCA (2015), and is considered as the "Baseline of soil degradation by erosion in Colombia" scale 1: 100,000 periods 2010–2011.	Water erosion Wind erosion	No erosion Nonsoil Light Moderate Severe Very severe	57.97 2.27 20 16.84 2.68 0.24

Data source: Based on different studies indicated in the table

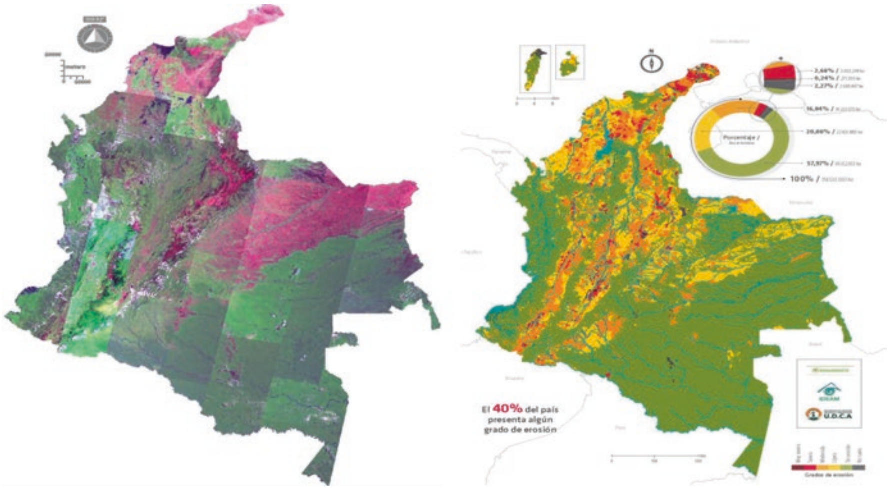


Fig. 9.12 On the left, mosaic of Landsat LDCM images 2016–2017 showing contrasts of areas with vegetation and bare soils (red) (Source*:* own work using Landsat USGS images). On the right, map of intensity of soil degradation due to erosion in Colombia (IDEAM et al. 2015)

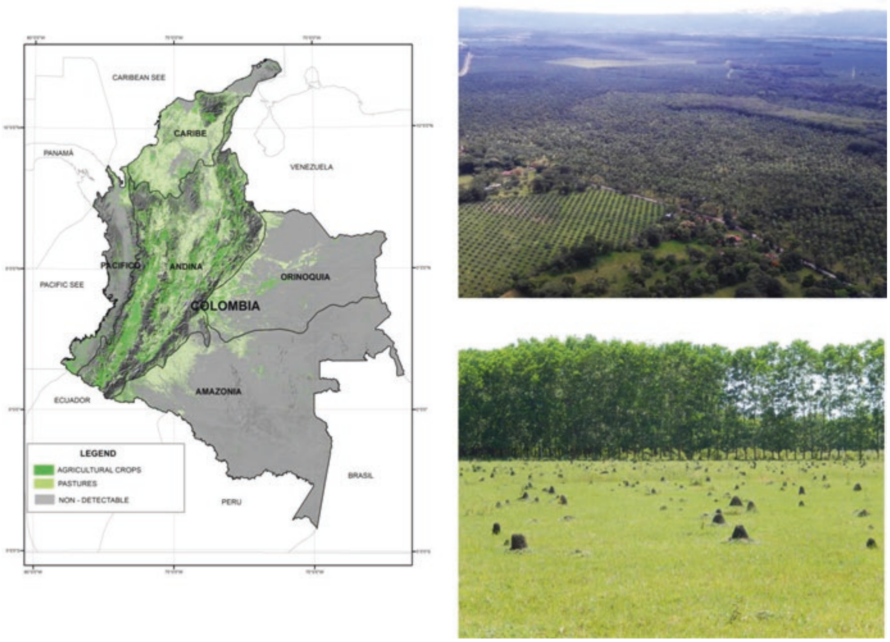


Fig. 9.13 On the left, map of crops and pastures in Colombia. (Modified from UNAL and IDEAM 2012; on the upper left, palm oil crops in the piedemonte llanero. Photo on the lower right, pastureland in the Orinoquía region)

of which 4.38 million hectares are in the Caribbean region (28%), 7.1 million hectares in the Andean region (46%), 2 million hectares in the Amazon (13%) and 225.788.5 hectares in the Pacific region (1%).

9.4 Social Impacts in Agriculture in Colombia Caused by Soil Degradation

A second issue addressed in this chapter consists of analyzing social impacts in agriculture caused by soil degradation in Colombia. The loss of soil in a given region of the world is the product of a network of multiple factors. Among these are factors that are related to decisions taken, to guide an economic model, that privilege one sector to the detriment of others. Those motivated by the situation of land tenure structure and those that are the product of natural processes also ought to be taken into account, topics that will be explored in more detail later. In Colombia, these causes are simultaneously associated with deforestation dynamics generated by the sowing of illicit crops, the intensification of sowing activities in smallholdings and the changes in use caused by mining and urbanization.

Related studies indicate that "Latin America and the Caribbean cover an area of 20.18 million km^2, of which 25% corresponds to arid, semi-arid and dry subhumid land. Of this total, in turn, 75%, about 378 million hectares shows serious problems of degradation" (Morales 2005; Meena and Meena 2017; Mitran et al. 2018). This situation is cause for great concern given that a significant percentage of the population, in the rural areas of these countries, earn their daily sustenance from activities related to the productivity of the soil for agriculture. In the cases of Argentina, Brazil, and Chile, it is indicated that of 222.014 productive units, the related percentages of desertified area vary between 15.7% for Brazil, 62.0% for Chile, and 75% for Argentina, with their corresponding incidence in the affected population, 19.5%, 22.1%, and 28.2%, respectively. The effect is demonstrated in the increase of poverty and misery indexes for populations that inhabit these territories in processes of degradation

It needs to be taken on board that, from a wider perspective, soil loss not only affects these rural sectors but has national and global implications since soil degradation puts at risk food security and sovereignty, biodiversity and related sociocultural processes, for example, the socioecological patterns of agricultural production, traditional knowledge and with these the possibilities for the existence of cultural diversity, as will be presented below.

In Colombia in particular, the social impacts arising from soil degradation are multifaceted, converging in certain regions of the country in combination with processes of structural violence and institutional weakness that are generally found in the far-flung rural areas of the country. This is a factor that hinders interventions to overcome them and generates serious situations of vulnerability for communities that have traditionally inhabited these places—mainly those that have traditionally had a direct relationship with the soil through agriculture and other related activities. In Colombia, rural areas historically have been traversed by the armed conflict of several decades, which has marked trends in its internal dynamics and in its relationship with the rest of the country: for example, isolated rural areas with problems of institutional weakness and a high concentration of the urban population in the central zone and the Caribbean coast.

9.4.1 Characteristics of the Population Affected by Soil Degradation

The social impacts of soil loss affect to a greater extent the population in vulnerable situations, in this case, people belonging to family units of agricultural production—the families of small farmers, or farming families. According to the FAO (2014), these small units produce 70% of the world's food. They total 2500 million families and constitute 83.3% of the population who live in the rural areas of the world.

Although there are discrepancies between the official figures and those of a number of scholars on the topic of productivity, Alfonso (2015) has calculated, for Colombia, losses in priority foods related to degrees of desertification approximated to 2,453,200 tons for the period in reference. In his study, however, he did not specify which sector of the rural structure is most affected. In the Colombian case, it is important to highlight that the social groups with a direct relationship with the countryside through small, family production units are peasant farmers, the indigenous communities, the Afro-descendants, the Raizal community. Official figures indicate that 10.3 million people in Colombia are peasant farmers (DANE 2013), a name given to people who have a direct and special relationship with the land through the production of food and other agricultural products. Specifically, these sectors work the land directly or depend on the workforce of their own family, practicing agriculture, livestock, transhumance activities and crafts related to agriculture. Peasant farmers are also considered people who do not own land (PNUD 2011).

This rural population is one of the social groups most affected by the soil degradation, whether caused by the cultivation of illicit crops, processes of mass movements and the described desertification, illegal mining, or the intensive use of land due to micro and smallholding conditions. According to (Morales 2005), on lands that are degraded or in process of deterioration, there is a higher incidence of poverty and indigence, since social and family structures are broken, given that the peasant economy depends essentially on family labor and they have a circle of production and consumption. Furthermore, because of their situation, they do not use technology for high productivity. With fewer crops or lower crop quality, they tend to intensify their use, which generates a greater deterioration of resources. In this scenario, adults migrate toward the search for new opportunities and in most cases, older adults, children, and some women endure situations of vulnerability.

For Colombia, the role of the peasant farmer as a provider of food to the cities has been documented, by such authors as Mosquera (2000), Ancízar (2011), mainly as suppliers of food for strata with least purchasing power. In effect, peasant farmers play an important role in food security since they produce food in areas where, due to topographic conditions, mechanization becomes difficult and with their products, they supply the demand of low-level consumers. They thus ensure the continuous and diverse supply of food for local markets. According to Forero (2003), agricultural products of peasant origin represent 68% of the country's total agricultural production. Therefore, where there is soil degradation, food that can supply this demand is not produced, generating greater vulnerability in the sectors of the population with the least income.

A second affected sector is that of ethnic groups. The National Agricultural and Livestock Census indicates that 750,000 people in Colombia who belong to ethnic groups (indigenous, Afro-descendant and Raizal) work permanently in agricultural production units (APUs). Of these workers, 58.6% are in territories of indigenous peoples, 41.1% in territories of Afro-descendant communities, and 0.3% in ancestral Raizal territory. An important issue to take into account and that the same census shows is that 32.0% of permanent workers are women, with greater participation in territories of indigenous communities. These communities, generally located in scattered settlements, register situations of poverty that aggravates with the soils degradation they use to cultivate traditionally and place them in a greater situation of vulnerability in the face of such factors as sociopolitical conflict and also in the face of natural events such as extreme El Niño or La Niña weather phenomena.

According to a National Planning Department report (2015), poverty levels are higher in the rural areas of the country, whether measured by income or by the Multidimensional Poverty Indicator (MPI). The scattered population considered poor or vulnerable exceeds 90%. Of this population, 11.5% older than 15 years is illiterate, a figure that rises to 17.4% for people who live in APUs. This is because not all lands located in the rural area are dedicated to agricultural or livestock activities. The departments with the highest incidence of poverty are Guajira, Vichada, and Guainía, with 84.6, 80.6 and 75.9%, respectively (Ministry of Agriculture-DANE 2016). These departments mainly host indigenous communities, generating consequences not only in their quality of life but in preserving cultural diversity.

The ethnic groups of Colombia are an important sector that is affected by the loss of land. DANE (2005) estimated that the indigenous population in Colombia for 2012 would be 1,392,623 individuals distributed throughout the national territory, the Amazon department being the territory with the largest number of indigenous people. An important aspect to highlight in relation to cultural diversity is that indigenous groups occupy a range of ecosystems from tropical forests to deserts, so in a broad sense, they do not compete with the rest of society regarding a given resource, although they live in different ecosystems they do it in a sustainable way. As such, it is considered that "indigenous people carry out many productive activities, among others gathering, hunting, fishing, and itinerant horticulture, activities of peasant economy such as agriculture and livestock grazing" (FAO 2015). If the ecosystems were adequately conserved, these groups could have autonomy in terms of their food supply and therefore in their food security and sovereignty. However, as mentioned below, a series of dynamics affects these conditions.

Afro-descendants represent 10.62% of the total population of Colombia, DANE (2005) estimate, concentrated mainly in the Pacific coast, the Caribbean coastal strip, Risaralda, Caldas, Quindío, and Antioquia. In the last decades, this population has undergone processes of displacement from their traditional territories. “The Constitutional Court in 005 of 2009 concluded, among others, the following causes of displacement of the Afro-Colombian population: 1. Structural exclusion that results in marginalization and vulnerability; 2. Mining and agricultural processes that impose severe pressures on ancestral territories; 3. Weakness in inadequate judicial and institutional protection of Afro collective territories” (United Nations High Commissioner for Refugees 2012). The processes of loss of their lands, and with the traditional patterns in relation to the land and its social nuclei, affect their ancestral links and traditional knowledge for the production of food; when they have had to move, they have been forced to break their traditional cultural practices and endure fragmentation of their social fabric.

9.4.2 Social Effects of Soil Degradation

Two separate scales of affectation in society due to soil degradation can be considered. One is the direct affectation of peasants, indigenous, and Afro-descendant communities. The other scale is related to society in general, due to issues such as the supply of food in local markets for the lower strata of the city.

Loss of Jobs Dedicated to Agriculture

In the first scale, related to peasant communities, deterioration in land use and the social situation of the peasants becomes a circular dynamic, since the use of agricultural land is changed for other uses, in most the cases the soil deteriorates even

Table 9.4 Number of permanent workers and average number of day laborers in APUs (Ministry of Agriculture-DANE 2016)

Extension of the Agricultural Production Unit (APU)	Total (APU) with permanent workers	Total permanent workers	% of workers who belong to the producer’s household	% of workers who do not belong to the producer’s household	Average number of wages contracted
Total	2.370.099	4.531.650	45,90	54,10	2,8
< 5 ha	1.699.798	2,648,965	53,00	46,97	1,9
From 5 to 10 ha	253.119	529,432	43,77	56,23	3,7
From 10 to 50 ha	327.913	832,182	38,61	61,39	4,7
From 50 to 100 ha	60.372	196,236	31,61	68,39	6,2
From 100 to 500 ha	47.607	216,234	22,78	77,22	8,8
From 500 to 1000 ha	5.488	41,950	13,25	86,75	12,0
From 1000 ha and more	5.842	67,459	8,95	91,05	10,2

further, expelling the population traditionally employed in agricultural use. Table 9.4 shows the number of workers engaged in agricultural activities.

From the previous table, it can be deduced that APUs with fewest hectares are those that require the greatest number of workers and, in the highest percentages, workers from the same home as the producer. This is because APUs with less than five hectares are less mechanized. The situation is very different for APUs with the largest areas in hectares that possess the highest levels of technology and are dedicated to the production of beef and dairy cattle. These are latifundios, large cattle ranches that require a low amount of labor. On these large ranches, the labor force is not family based, and instead, the percentage of external persons hired increases, as does the percentage of day laborers. “In 2009, the productive vocation to devote the land to livestock has an overuse of 28.2 million hectares, of which 17.3 million hectares is rested for use in agriculture and 9.1 million hectares devoted to forestry” (Ancizar 2011; Yadav et al. 2018; Meena and Lal 2018).

According to this information, it is possible to speak of fragmentation of agricultural dynamics. Many of the soils that by vocation ought to be dedicated to agricultural production are being used for livestock, for the obvious economic advantages that this sector has. For the agricultural sector, however, one of the main obstacles that affect the productivity of traditional family farming is the scarce or complete lack of access to productive assets: four assets specifically, according to a report by the National Planning Department (2015). These are access to lands, technical assistance, credit, and on-farm irrigation. Some 63% of rural inhabitants had no access to any of these, and less than 2% had access to all of them. Agricultural production, therefore, becomes unsustainable, leaving family production units at a disadvantage compared to large-scale production—mainly monocultures or livestock.

9.4.3 Soil Deterioration, Food Security, and the Loss of Cultural Diversity

Soil degradation has also been found to be related to loss of biodiversity, resulting in the destruction of vital ecosystem services and the degradation of the landscape. This affects acculturation processes since communities must dedicate themselves to other trades to maintain their basic income, or migrate to the cities. Loss of ancestral practices and beliefs negatively affects the consolidation of alternative processes to development. These effects generate greater vulnerability to climate variability and change, phenomena that in recent years have generated disasters in the country. When such soil degradation occurs, many farmers tend to use agrochemicals that can damage the soil further. From the sociocultural point of view, according to Ancizar (2011), a dependence on agrochemicals is generated, with repercussions in the decrease of the family income, health problems in producers and consumers due to misuse of inputs, and an effect on traditional technologies and practices.

Statistics from the Ministry of Agriculture-DANE (2016) indicate that in 70.2% of the scattered rural area surveyed, fertilizers were applied to improve the soil, with the problems of dependence and environmental impact already mentioned. Some also use organic fertilizers, so that 46.5% of APUs use organic fertilizers; 2.5% burning and there is a lower percentage, approximately 15% that uses payments, prayers, and rites to improve soil productivity, the latter according to their cultural traditions.

In relation to soil care, in 75.2% of APUs surveyed, producers declare that they carry out soil protection activities, among which 45.9% practice leaving the remains of stems and leaves after cultivation to avoid erosion and landslides, 29.4% minimum tillage and 28.7% manual sowing without using machinery or removing the soil; 79.2% of APUs use animal and vegetable waste to fertilize the soil (DANE 2014).

A topic closely related to soil deterioration that has consequences in the medium term is the loss of food security. Thus, when breadbasket productivity drops, they resort to processed foods, diversity is lost, and a process of deterioration of associated sociocultural practices is initiated. In general, 42% of Colombian households perceive themselves to be in a situation of food insecurity, that is, consider that their food is not guaranteed in adequate quantity and quality (FAO-Department for Social Prosperity 2015).

The Colombian State, in 2008, adopted the following concept for the definition of its Food and Nutritional Security policy, as: “the adequate and stable availability of food, access and the prompt and lasting consumption of these in quantity, quality and safety for all the population, under conditions that allow their proper biological use, to lead a healthy and active life” (National Planning Department-CONPES 2008). The document points out that there is instability in the sufficiency and supply of food. Colombia increasingly imports more food and has problems concerning its internal distribution. There are access difficulties for such distribution in geographically remote areas and these also lack the right conditions for diversified production.

In terms of food production, the National Planning Department-CONPES (2008) points out that agricultural production can be affected at the regional and local level by the use of productive factors such as soil and water, genetic resources such as seeds and financing, the efficiency in technology, and the capacity of the country to face climatic risks. Regarding land use, this is related to the concentration of property and conflicts of use that as we have shown deteriorate the soil.

Nongovernmental organizations go beyond the official approach. They believe that the concept and approach of food security should transcend the individual perspective and ensure a broader cultural context of a collective nature and therefore must consider other factors that transcend the issue of individual satisfaction. “Food sovereignty is the right of people, their countries or unions of States to define their agricultural and food policy without having to sell to third-party countries at reduced prices” (La vía Campesina 2003; Meena et al. 2018). This element is of vital importance to understanding the relationships between agricultural production, autonomy, and development models.

From a perspective related to collective values, the indigenous, meanwhile, identify with a concept of food sovereignty oriented to the territorial protection with a community character that claims their rights related to food, self-determination, and the defense of cultural heritage. Hence, explicitly, food sovereignty is related to their religious beliefs, their rights to the territory, their livelihoods, and autonomy as a community (FAO-Department for Social Prosperity 2015). It should be noted that despite these important policy instruments, the situation of some sectors of Colombian society presents negative indicators in relation to access to food; for example, the data shows that 47.6% of indigenous people do not have the income to acquire a basic food basket (INDEPAZ, Institute for Development and Peace 2009).

In essence, loss of land generates in small communities of peasants, indigenous people, and Afro-descendants a reduction in access to the food they are accustomed to eating in their daily diet. This affects particularly the indigenous and Afro-descendant communities, who confer an ancestral cultural value to their food, as foods are produced through practices and rituals learned collectively, practices that give them a sense of collective identity and allow the existence of cultural heterogeneity.

Thus, the loss of land, not only affects the food supply, but the cultural diversity and, with this, the ancestral knowledge that Western society could use to its benefit with more sustainable practices in favor of the environment.

9.4.4 On Soil Loss and Population Displacement

The displacement issue is especially important in Colombia, given that there is often a greater emphasis on forced displacement generated by violent conditions, in which large numbers of people are stripped of their lands. While clearly recognizing the importance of those occurrences, in this document we will refer to displacement generated by the loss of land due to a change in use that is motivated by a public policy decision. Soils thus traditionally destined for agriculture are then used for infrastructure works or power generation, as in the case of hydroelectric plants.

Castles (2003) has called this phenomenon “displaced by development”, to demonstrate the fact that people are forced to move through the construction of large-scale infrastructure projects such as hydroelectric plants, airports and other projects of the governmental interest. In Colombia, such displacement is all too evident. An example is the construction of the Urra hydroelectric plant, which brought with its important environmental impacts. This dam mainly affected the Embera indigenous people, peasants, and fishermen, who had to change their traditional activities related to natural dynamics. A number of documents indicate the perceptions of the population on these impacts; “The people of the basin, the countryside, and the city saw how the banks of the river eroded and permanently destabilized with the sudden changes in the flow of the river caused by the operation of the dam” (Rodríguez and Orduz 2012; Buragohain et al. 2017; Layek et al. 2018).

It is estimated that as a result of the work carried out related to the dam and all the dynamics that took place in the region, approximately 30,000 people were displaced. As pointed out by Castles (2003), this type of intervention has millions of the population of the world impoverished and in a situation of social and political marginality, because, according to the author, “dams are built in remote areas inhabited by indigenous people or ethnic minorities. It is usual for such groups to practice extensive forms of agriculture and to have deep links with their ancestral land" (Castles 2003). With this type of intervention, these links are lost and, as in the case of the Embera, people have little choice but to migrate toward the cities.

There is currently a discussion about what some researchers have called "environmental displacement", to characterize the population displacement caused by the loss of quality in the environment. This approach takes account of those population displacements related to desertification, deforestation, land degradation, contamination of water sources, and those related to natural disasters. However, the conceptual relevance of the approach does not allow us to understand that this type of displacement corresponds structurally to problems related to the sociopolitical conflict, which has implications for the environment (Castles 2003). In the case of Colombia, the confluence of a series of factors can be identified that lead the settled population in a certain region to move, as a consequence of insecurity and the loss of their lands, due to causes such as coca cultivation, illegal mining and other changes in the environment that generate displacement of the population that traditionally occupied those lands in agricultural and livestock activities.

Most affected by the displacement, in the majority of cases, are members of ethnic groups and peasant communities, who must leave their lands abruptly and move to nearby cities. A report by Ibañez and Velasquez (2008) notes that ethnic groups are the most affected since they have economic losses due to the displacement but also have a loss of their cultural traditions and practices. The source points out that the 8.2% of the displaced population in the country comes from these groups because they have their lands in conflict zones but also because armed groups probably want to use the land for their own activities.

As the conflict is most prevalent in rural areas, population displacement in Colombia occurs from rural areas to cities. When families move, they lose their land and with this their way of life. Their knowledge and practices related to the agricultural sector are not of interest in the urban labor market so that their vulnerability increases. As they know little of the ways of the city, they invariably swell the informal sector of the economy in a quest to obtain the income that will allow them to subsist.

Ibañez and Velasquez (2008) estimate that before displacement 21.8% of the displaced population was engaged in agricultural and livestock activities and, to a less extent, in trade and services. In their new situation of displacement, they are engaged in informal activities—67% of women and 47% of men, earning less than a minimum monthly wage since rural land and human capital are not valued in the new scenario. The immediate effect is low income and food insecurity, given that being people from rural areas who produced their own food, in the new reception areas they do not manage to comply with a basic diet that meets their nutritional requirements.

9.5 Economic Context and Soil Degradation in Colombia

The third part of this chapter addresses some of the economic and sectorial dynamics that have characterized the country, their effects, and impacts on soil degradation processes in Colombia. It is important to clarify that some of these processes that will be dealt with subsequently result in deterioration and degradation of the soil, which in turn produces alterations in agricultural production and socioeconomic dynamics in the different regions of the country. For the purposes of this section, only those that are considered to cut across soil degradation processes in the last decades in Colombian territory will be dealt with, as follow.

9.5.1 Land Ownership, Soil Degradation, and Effects on National Production

In the recent research on soil degradation in Colombia, little importance is assigned to its relationship with land ownership. However, the most comprehensive studies, especially from academia, lead us to affirm that the structure, tenure and ownership patterns of the land in the last 60 years in the country are central when it comes to revealing the true extent of the current state of soils and the possible mechanisms for their sustainable management.

From analysis of cadastral information for 1977–2016 provided by the Agustín Codazzi Geographical Institute (IGAC) (León et al. 2012) from the 2014 Agricultural Census conducted by the National Administrative Department of Statistics (DANE), with the restrictions that can be demonstrated in the definition of ownership of many properties that were linked to 60 years of violence in Colombia, it is possible to establish that small property (as defined by UNDP and assumed in this chapter as property of less than 50 ha)—which for 2011 accounted for 33.0% of the total area—was in the hands of 87.2% of owners; while for the same year, 28.5% of the territory corresponded to properties of more than 500 hectares, as seen in the following table, were concentrated in 1.5% of owners.

Under this same categorization, following Table 9.5, there is a decrease in the units of medium size as well as in the number of owners for the years 2014–2015. While registering a high number of owners (93.2%) that own about 18% of the total area of the national territory, in small properties of less than 50 ha (a relationship that demarcates an overuse of soils) they correspond particularly to the Andean region, which concentrates the largest proportion of the Colombian population. Following the information provided by the table, it is striking that close to 60.1% of the total area of the country is in the hands of only 0.6% of owners (Table 9.6).

These figures show a deepening of the trend that has marked agrarian history and land tenure in Colombia, where some owners are found to have little productive land, corresponding to areas that have undergone processes of transformation, overuse and accelerated deterioration of the soils, expressed in degradation of these, of productivity, lower production and lower levels of competitiveness of zones with crop use destined as foodstuffs. These areas have in turn been the scene of anthropic

Table 9.5 Property size in Colombia, 2011

Range	GINI Land	Área		Propiertiers		Owners	
		Ha	%	No.	%	No.	%
Small (<50 hectares)	0,61	12.687.945	33,03	2.360.488	94,70	3.147.189	87,26
Median (50 ha <500 hectares)	0,21	14.770.086	38,45	123.997	4,97	402.902	11,17
Large (>500 hectares)	0,30	10.957.770	28,52	0.230	0,33	56.542	1,57
Grand total	0,86	38.415.801	100,00	2.492.715	100,00%	3.606.633	100,00

Adapted from UNDP (2011)

Table 9.6 Property size in Colombia, 2014–2015 (Calculations 2018, from information in IGAC 2014 and UPRA 2015)

Range	GINI Land	Área		Propiertiers		Owners	
		Ha	%	No.	%	No.	%
Small (<50 hectares)		13.336.000	18.0	1.546.920	93.5	2.360.331	93.2
Median (50 ha <500 hectares)		16.312.000	1.9	99.003	5.9	156.789	6.2
Large (>500 hectares)		44.791.000	60.1	6.933	0.42	13.904	0.6
Grand total	0,73	74.439.000	100,0	1.652.866	100,0	2 0.531.024	100,0

effects throughout the history of the country, reflecting a greater fragmentation and deterioration. They are located mainly in the Andean region, where a variety of conflicts for land use converge.

These territories, constituted by small properties characterized by the presence of peasant economies, face the loss of soil quality together with territorial conflicts, due to changes in use to make way for other activities such as conversion to pasture land (Fig. 9.13), mining, agro-industrial development, urban expansion and consolidation, leading to true sealing processes of territories with agricultural vocation; processes that are framed in the trends of the global and regional economy, in the development models that have characterized public policy in Colombia, especially economic, sectoral, and territorial policies. These phenomena are reflected in a decrease of agricultural production, affecting regional, national food security, and economic policies in terms of trade that have led in recent decades to food importation processes, to a loss of sovereignty and of food security, affecting the quality of life of the populations that previously produced food surpluses. As indicated by UNDP, the agricultural sector in Colombia represented 12% of the GDP (gross domestic product) in the 1970s. In the year 2000, this decreased to 8.6% and in 2014 fell to a level of 6.8%.

In addition to the reasons presented here for other areas of the country where major land use changes are occurring, such as the Orinoquia and the Colombian Amazon, characterized by informality in land tenure rights—derived in large part from the confluence of the armed conflict, drug trafficking in these regions, the processes of forced displacement, environmental displacement, dispossession, abandonment and usurpation of lands due to violent causes, they turn into difficulties in defining the legal status of large tracts of land in these rural areas, together with the arrears registered by the cadastre offices in these regions. (CONPES ORINOQUIA 2014).

Imbalances and effects on the quality of the soils are also associated with inadequate uses of the soils that do not consult their characteristics and their vocation or agroecological aptitude, a prerequisite for their sustainability over time. Based on work done by IGAC (2012) on land use in Colombia and the references defined by the recent soil policy in Colombia (2016), it is possible to consolidate the base information of land vocation by region, in Table 9.7.

Despite the disaggregation of the information in the previous table and how it can be evaluated in the following cartography, the current use of the land does not correspond to its aptitude, a situation that has led to effects on soil quality, levels of production and productivity. The advance on forest areas to make way for deforestation destroys land cover, leaving soils at risk of degradation due to erosion, loss of biodiversity, of biota organic matter and of soil water. The average annual deforestation for the 2005–2010 period, according to IDEAM (2010), was estimated at 238,000 hectares, with large losses of natural forest, mainly in regions such as the Amazon, the Andean region and some gallery forests of the Colombian Orinoquia; a great part of these territories gave way to areas destined to pastures. It should be noted here that some pasture conversion processes that occurred in the Colombian territory were driven by the processes of armed conflict. Thus, we find spaces

Table 9.7 Areas of agricultural production, livestock, in Colombia by region

Vocation group	Area (ha)	% total area	Geographic región
Agricultural	22.077.625	19.34	Andean region, 6.5 million hectares; Caribbean, 5.0 million hectares; Orinoquia, 4.6 million hectares
Livestock	15.192.738	13.31	Intensive, semi-intensive grazing on 40% of the cattle-raising land and 60% (9.1 million hectares.) suitable for silvopastoral-type agroforestry uses; of which Orinoquia region, 4.04 million hectares; Amazon, almost 4.7 million hectares; Caribbean, 2 million hectares; and Andean region, 1.2 million hectares
Agro-silvopastoril	4.057.776	3.55	Land suitable for transient and permanent crops combined with woody arboreal components, totaling approx. Seven million hectares, located in the Amazon departments such as Amazonas, 2.03 million hectares; Caquetá, 937.000 hectares; Vaupés 601.000 hectares; and the departments of Chocó, 600.000 hectares and Meta and Guainía with more than 200.000 hectares
Forestry	64.204.294	56.23	Located in the Amazon, 28.8 million hectares 25.3% of the country); Andean 21.301.271 hectares (18.6%); Orinoquia, 10.2 million hectares (8.9%) and Caribbean, 3.7 million hectares, (3.8%)
Soil conservation	6.303.503	5.52	Corresponds to conservation of water and hydrobiological resources and to recovery; the Andean region has almost half of the land for the protection of natural resources, due to its orographic complexity
Body of water	1.935.201	1.69	
Urban and other areas	232.791	0.35	Sealing of areas by urban expansion and establishment of infrastructure. Correspond to sealing zones due to urban expansion
Total	**114.174.800**	100.0	

Modified from National University of Colombia (2016a, b, c)

converted into pastures that occupy territories that formerly had agricultural and forestry aptitude, generating negative externalities in the soil, at the same time leading to conflicts due to their use (where their aptitude is not taken into account), to degradation and in some cases to effects of irreversible character and replacements that economically and environmentally are not viable.

In a complementary manner, the UNDP draws attention to the use of soils compared to their true vocation by pointing out:

The information provided by the National Agricultural Survey (ENA) for 2008 indicates that, in 25 of 30 departments, more than 50% of the agricultural frontier is used in pastures, and that in 16 of them more than 70% of the land is in livestock. According to the IGAC, the land suitable for livestock and silvopastoral activities amounts to 21.1 million hectares, and today 39.2 million hectares are used (including weeds and stubble); that is, it would be necessary to release at least a total of

10.6 million hectares if we only consider what is actually used in livestock, which is 31.6 million. A more realistic figure would indicate that the land with a pure livestock vocation, which is 15 m ha, would be compared with the 31.6 million hectares used. That is, the release of land for agriculture and forestry activities would reach close to 15 million hectares, since the use in silvopastoral activities is practically marginal. (UNDP 2011).

However, areas that should be used for conservation and recovery are rarely recognized. Therefore, in order to achieve a balance between conservation and production in Colombia, approximately 87 million hectares, equivalent to 76.3% of the continental area, require to be adapted and protected. Of these, 18.348.745 hectares are under some category of the protected area, corresponding to 16.1% of the national territory, figures that demand the declaration of other areas for protection and conservation.

It can then be affirmed that the cadastre of the end of the twentieth century and the decades of the twenty-first century and the recognition of the Colombian territory account for a duality in land ownership in Colombia: First, the concentration that led to true processes of relatifundización, or division of land into large estates, that manage to consolidate an agro-industrial, monoculture and commercial model supported in the model of the so-called green revolution, with effects on the degradation of soils, on the loss of biodiversity, to the detriment of production, diversity and food sovereignty, to give way to specialization in the products demanded by the markets; displacing the population in search of new territories and improvements in their quality of life. Second, the peasant economies that produce food develop in small properties, putting pressure on the quality of the soils, especially in the Andean area. Together with this process, the leasing of land for production becomes a dominant modality for agricultural production, but with serious impacts on the soil and the environment. Consequently, conventional tillage of the soil, the transit of machinery, and the trampling of cattle constitute activities that in Colombia represent a high risk of degradation in soils that are suitable for agriculture.

9.5.2 Transformation of Strategic Ecosystems and Soil Degradation

Among the strategic ecosystems in Colombia are the moorlands, known as a unique neotropical high mountain biome found in few countries in the world. Moorlands are of high value for their biodiversity. Their soils have a high organic matter content and a high capacity for water and nutrient retention. Ecosystem benefits derived from their functions affect welfare levels, with their regulatory functions being the most relevant. Colombia hosts about 39.4% of the moorland of South America, occupying about 1.405.765 hectares.

The research carried out by the National University in the last 10 years in the moorland of Colombia, in particular those of the Colombian oriental mountain range (Chingaza, Guerrero-Rabanal, Cundiboyacense Altiplano, Iguaque, and Merchán), confirms that it relates to territories that have also been transformed

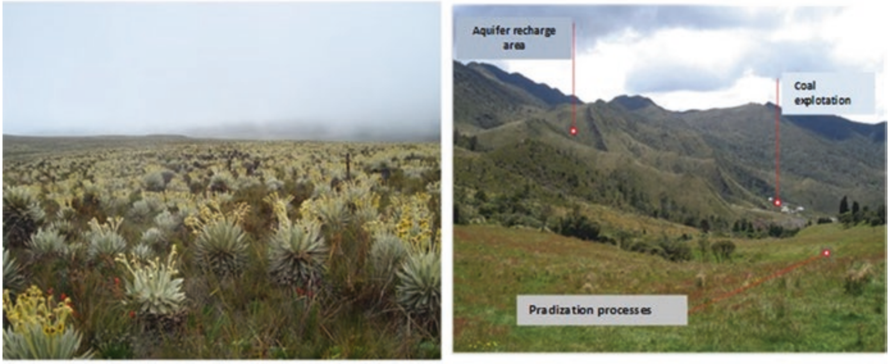


Fig. 9.14 The Guerrero moorland: transformation of a strategic ecosystem (National University of Colombia 2010)

(Fig. 9.14) by the different societies that have advanced and expanded the agricultural frontier unbalancing such ecosystems, in particular by altering their biodiversity, native vegetation, characteristics, and soil properties, reaching a level of degradation and compaction particularly associated with those that register a high level of sowing pasture grasses. Agricultural use is characterized by rapid colonization, which, under the technological model supported by the intensive use of agrochemicals, generates strong impacts in changes of plant cover, soil, water mirrors, and the environment in general. In some of these moorlands, such as Guerrero, it can also be seen that the soils marked by this deterioration are translated in decreases not only in the levels of production but also in productivity, leaving small proprietors and tenants to confront a loss of competitiveness especially in this market.

Other extractive activities have been established in these territories, as in the case with tunnel coal mining, generating not only transformations but also impacts on the territory.

Information derived from spatial analysis (1970–2016) carried out in the moorland in the Colombian eastern mountain range indicates that in the Cundiboyacense Altiplano complex, the moorland coverage suffered an intervention of 13.72 ha, equivalent to 9.12% of the surface of the coverage reported within the moorlands complex in 1977. The Iguaque-Merchán moorland complex showed an intervention of 2.066.58 hectares, equivalent to 22.51% of the moorland cover analyzed for 1977 (Fig. 9.15).

After this dynamic of 37 years of change, it is observed that the smallest remnants of the moorland complex of the Cundiboyacense Altiplano are conserved in the hamlets of Gacal (Samaca), Bojirque (Ventaquemada), Faracía-Pantanitos (Lenguazaque), Montoya (Ventaquemada), and San José (Gachancipa). These hamlets, besides being the ones with the smallest remnants of the whole complex, also show that since 1977 these relicts have been preserved. For the Iguaque complex, the hamlets with the smallest remnants are Duraznos and Colorados (Santa Sofía), Puente de Tierra, Pantanos (Savoy), Gaunza Arriba (Sotaquirá), and Cañón (Sutamarchán). Of these,

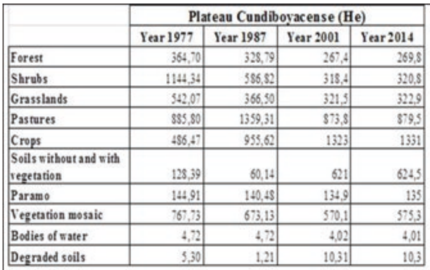
Fig. 9.15 Some extractive and productive activities in moorland areas (National University of Colombia 2010)

Puente de Tierra is the hamlet that has undergone the greatest transformation. For 1977, it had an area of 8.78 hectares, and for 1987 it had 0.90 hectares, a loss of 89.7% of its coverage. It is essential to focus on these hamlets' conservation actions and sustainable management of the productive moorland, in order to avoid the disappearance of this vital coverage, fundamental for water and soil.

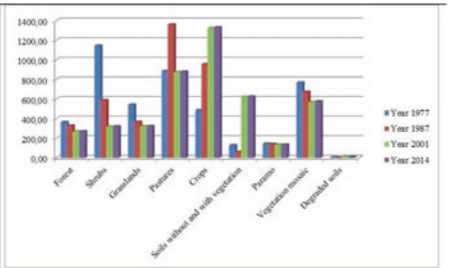
To carry out the spatial transformation analysis, the coverages obtained from aerial photographs and satellite images were combined for pairs of decades, in the continuum 1940–1977–2014. To carry out the analysis of the transformation of vegetation cover, some coverages were generalized and differentiated as a result of the classifications of the images. Table 9.8 summarizes the transformation processes of the Iguaque-Merchán and Cundiboyacense Altiplano Moorland complexes for the period 1977–2014; following these results, it is observed that for the case of the Cundiboyacense Altiplano, there was a large reduction in hectares of forest, as well as hectares of moorland and natural vegetation, processes that demarcate the fragmentation of these moorland territories as they are usually evaluated today. In the meantime, there was a gain or increase in the hectares destined for pasture that led to the compaction of the soils and to the expansion of the agricultural frontier for the production of potato monoculture, deteriorating the biodiversity present in these soils. Likewise, the hectares of soils with little or no vegetation increased, just as degraded soils doubled during the analysis period, a figure that is derived from the transformation model that was followed in these spaces.

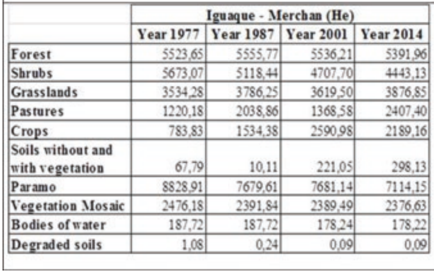
The Iguaque-Merchán moorland complex underwent heavy transformations, as shown in Table 9.8. During the period of analysis, it also suffered a decrease in forest areas, in the mosaics of natural vegetation and in the moorland areas, changes that call for means of appropriation of these sustainable territories. It is also worrying that the areas of savanna and grass-sowing or pastures doubled, while areas for crops tripled, with the collateral increase of hectares of soil with little or no vegetation, with consequential loss of soil quality.

Table 9.8 The transformation processes of the Iguaque-Merchán and Cundiboyacense Altiplano Moorland complexes for the period 1977–2014 (Universidad Nacional de Colombia 2016a, b, c)

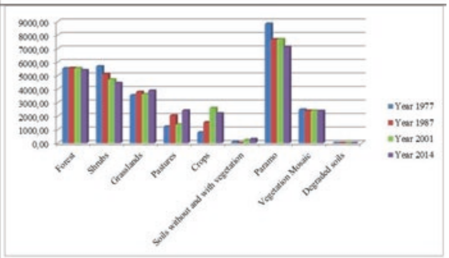


	Plateau Cundiboyacense (He)			
	Year 1977	Year 1987	Year 2001	Year 2014
Forest	364,70	328,79	267,4	269,8
Shrubs	1144,34	586,82	318,4	320,8
Grasslands	542,07	366,50	321,5	322,9
Pastures	885,80	1359,31	873,8	879,5
Crops	486,47	955,62	1323	1331
Soils without and with vegetation	128,39	60,14	621	624,5
Paramo	144,91	140,48	134,9	135
Vegetation mosaic	767,73	673,13	570,1	575,3
Bodies of water	4,72	4,72	4,02	4,01
Degraded soils	5,30	1,21	10,31	10,3





	Iguaque - Merchan (He)			
	Year 1977	Year 1987	Year 2001	Year 2014
Forest	5523,65	5555,77	5536,21	5391,96
Shrubs	5673,07	5118,44	4707,70	4443,13
Grasslands	3534,28	3786,25	3619,50	3876,85
Pastures	1220,18	2038,86	1368,58	2407,40
Crops	783,83	1534,38	2590,98	2189,16
Soils without and with vegetation	67,79	10,11	221,05	298,13
Paramo	8828,91	7679,61	7681,14	7114,15
Vegetation Mosaic	2476,18	2391,84	2389,49	2376,63
Bodies of water	187,72	187,72	178,24	178,22
Degraded soils	1,08	0,24	0,09	0,09



It is important to recognize that the time interval with the greatest transformation rate is 1977–1987 for the Iguaque-Merchán complex. Although these rates decreased in the other two pairs of dates, for reasons of property and land tenure, through the declaration of protected areas, and for economic reasons, the accentuated differences between social groups are still significant and dangerous for the remnants of moorland conserved in the sector, especially in the Altiplano complex. In those hamlets where remnants of the greatest extension are conserved, it is also essential to adopt action plans toward the conservation of the soils of these strategic areas, for the production of water and the habitat of numerous species.

It is important to mention that recently, the Ministry of the Environment and Sustainable Development (2018) in Colombia issued a series of environmental regulations, directed in the first instance toward defining measures to determine the settlement spaces of the communities traditionally linked to construction of these territories and their sustainability and, secondly, to establishing regulatory mechanisms to protect these strategic ecosystems with a view to restoring the environmental benefits or services that derive from their functions, especially in the regulation of soil, water, and climate. It has been constituted in a requirement beyond being merely regional, due to its importance and effects at a global level. These measures will need to be implemented especially in those moorland areas where it is feasible to ensure their ecosystemic integrality.

As indicated at the beginning of this section, soil degradation processes in Colombia have become an issue of relevance in the dynamics of the territories, but they become perhaps even more important because of the effects they have on the socioeconomic dynamics. Economic and territorial policies in turn tend to generate changes in the soil. In this context, the analysis that follows is derived from the implications of macroeconomic policies and development models in the processes of land degradation in the national geography.

9.5.3 Macroeconomic and Sectoral Policy and Development Models

As the OECD (2015) points out, during the 1990s, Colombia started to open and introduce a liberalization scheme of the countries' economy based especially on the elimination of restrictions on foreign trade and the reduction of tariffs, accompanied by other policies in the financial and labor sphere, among others, which to some extent registered positive balances in the economic growth of the country, especially at the end of the twentieth century.

The Extractivist Development Model

On analysis, the macroeconomic and sectoral policies through the development models that have characterized the country—especially the extractivist model of natural resources: mining-deforestation since the beginning of the twenty-first century—lead to a profound change in the use of land and a loss of optimal areas for food production, due to soil degradation and contamination. As indicated by Rudas (2010), derived from the contrast between the Atlas of moorland of the Von Humboldt Institute, 2007, and the map of mining titles reported by Ingeominas in 2009, titles were at that time registered in 122.000 hectares representing 6.3% of the total of the area in moorland identified in that atlas. The highest growth of mining titles then took place between 2007 and 2009, with more than 52.000 new titled hectares.

Under these contextual considerations, the composition of Colombian exports clearly reflects the way in which dependence on mining products was promoted. From 38.2% of total exports, these accounted for 67% in 2013, as can be seen in Table 9.9.

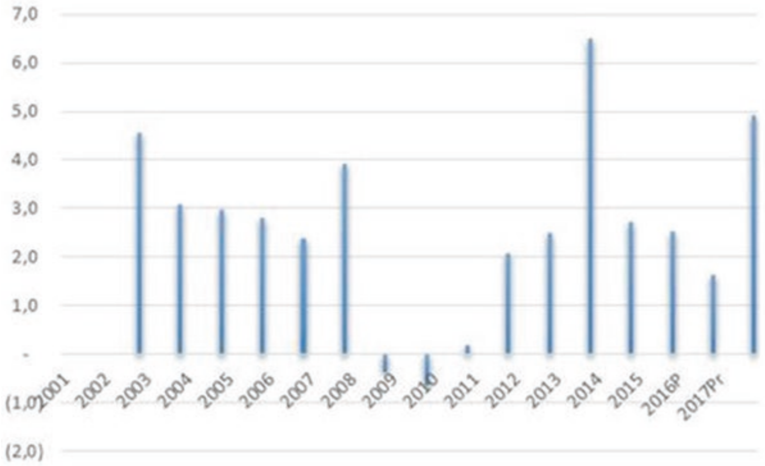
At the end of the last century, Colombian politics adopted an economic model based on exports of primary goods. However, the signing of FTAs (Free Trade Agreements) led to an increase in imports, especially of food. As pointed out by Zerda (2015), for the period in question, about 23% of the national food basket was imported, reflected in the deterioration of sectoral participation in GDP by about five points for 2015, as can be observed in Graphs 9.1 and 9.2.

Looking at the trend over the last 15 years, the agricultural sector was seen to grow above the national economy in only two periods, which will be explained later. In part, the loss of dynamism and participation of the sector in the national economy is explained by the rise of other sectors in recent years, such as the mining-energy sector, which has largely exceeded agricultural and industrial exports, especially in the last 6 years (MinMinas 2013). In addition, the tertiary sector, mainly in

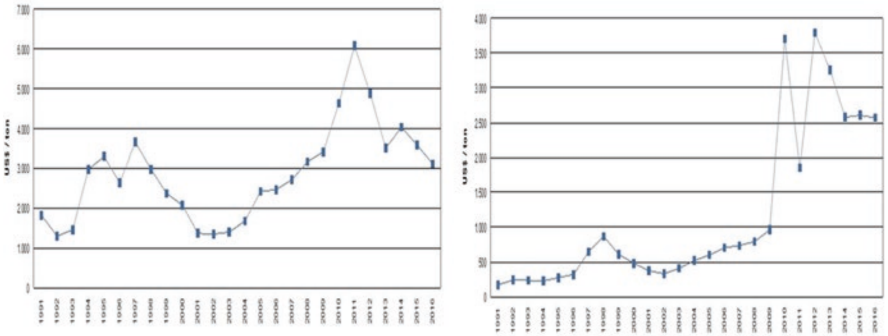
Table 9.9 Rate (%) of sector participation in Colombian exports, 2002–2015

Year	2002	2004	2006	2008	2010	2011	2012	2013	2014	2015
Farmer	21.4	20.7	20.2	17.8	14.5	12.4	11.0	11.4	13.4	18.4
Mining	38.2	39.3	40.8	48.0	58.4	66.1	66.7	67.9	66.5	57.0
Manufacturers	36.1	35.8	35.6	31.5	21.7	16.1	16.6	16.9	17.1	21.8
Other	4.3	4.2	3.4	2.8	5.4	4.9	5.7	3.9	3.0	2.8

Adapted from Zerda (2015)



Graph 9.1 **Total** GDP vs agricultural GDP for Colombia 2001–2016 (DANE 2018)



Graph 9.2 Colombian exports of coffee and potatoes, 1991–2016 (data from Agronet 2018)

Colombian cities, has largely driven economic dynamics with the boom in business, personal and financial services, transportation, and construction, while the manufacturing and agricultural sectors have lagged behind (OECD 2015).

Moreover, observing the behavior of indicators of the agricultural sector shows that during the period from 1987 to 2016, the general behavior has been irregular, with periods of growth and decrease both in harvested area and in levels of production and yield. The exception was 2007, in which there was an increase in production of about 78%, while the increase in harvested area was only 13.8%, having a significant effect on yield per unit of hectare harvested. This behavior is explained by the increase in the value registered in the production of sugarcane in Valle del Cauca, whose dynamism could be explained by the increase in the production of fuel alcohol, intended for “mixing with gasoline in a proportion E8 (8% ethanol, 92% gasoline), in accordance with the mandate of oxygenation established by the government since November 2005" (ASOCAÑA 2017). For 2007, the production of sugarcane increases remarkably and reaches a participation rate of 49% of production. This behavior is also reflected in the growth of agricultural GDP in 2007 (Graph 9.1), which was not exceeded until 2013.

The national accounts provide trends in the loss of participation of the agricultural sector in total GDP, placing difficulty in the food security of not only rural but urban populations that depend on the sector. The intertemporal analysis of the agricultural censuses and their projections in the short term account for the behavior and the impact on the levels of productivity, the deterioration in the terms of trade, foreign exchange earnings, and the lower contribution of the agricultural sector to the growth of the Colombian economy.

Coffee production and exports are losing their participation in total exports. This subsector is no longer the main generator of foreign exchange for exports, compared to the high participation of hydrocarbons and mining exports. This is a behavior that is largely explained by the macroeconomic policies chosen by the country based on the motor driving the mining industry, failing to provide policies favorable to the coffee sector. Of course, global trends have also been accompanied by the high volatility of international hydrocarbon prices.

Potato production, one of the most relevant products in the food basket of Colombians, has decreased due to changes in the agricultural frontier and replacement with livestock, changes in the state of some ecosystems, the absence of labor in production zones, contraband of the product, and the mining-energy boom, which marked the deterioration in the terms of trade with irreversible effects in some production areas of the peasant economies.

In general, the performance of the sector in the 1990s can be classified as poor, especially in the harvested area indicator (ha), explained by such factors as the drop in international prices, the economic opening, the revaluation of the exchange rate, the high interest rates, and others such as rural violence and drought in 1992 (Aguilera et al. 2017; Meena et al. 2016; Gogoi et al. 2018). The twentieth century ended with a negative growth rate of both harvested area and production per ton in 1998, perhaps explained by the serious economic and financial crisis that the country went through in the 1998–1999 period (OECD 2015).

On the other hand, according to Pérez and Pérez (2002) "between 1991 and 1998, the area dedicated to transitory crops such as rice, corn, sorghum, barley and wheat, among others, decreased by more than 875,000 hectares" because of the negative effects of "the drastic economic opening policy" that allowed the importation of fresh and processed agricultural products at lower prices from economies of scale. The twenty-first century began with a moderate growth in the agricultural sector until 2007, as explained above. For the year 2008, the international financial crisis adversely affected production in tons (not the harvested area) and agricultural GDP (Graph 9.1). "Likewise, the strong appreciation of the currency during the period 2008–13 associated with the importance of natural resources has also affected the competitiveness of the agricultural sector" (OECD 2015).

In addition to the decline in agricultural exports in those years, the rainy season that began in 2009 and worsened in 2010 negatively affected production and GDP in those years. Later, the atmospheric phenomenon of La Niña intensified for 2010–2011, generating a winter wave in almost all the national territory, affecting notoriously the production of the agricultural sector. As a result, in 2010, the sector faced a fall of 5.5% in production per ton, according to Agronet data, added to a growth in agricultural GDP close to zero, according to data from national DANE accounts (OECD 2015).

The years 2011 and 2013 bounce back with a significant recovery, so much so that the agricultural sector exceeded the growth rate of the national economy in 2013–2014 (Graph 9.1). This could be explained in part by the public policy of the sector in those years. Between 1992 and 2011, state transfers in the form of market price support had been relatively small. However, in 2011–2013, they increased strongly to constitute 19% of the producer support estimate. Although coffee continued to be the most important crop in terms of area harvested in 2007, the fact is that this product has been losing relevance in the national economy, due to the breakdown of the international coffee pact in 1989 and the increase in other exportable permanent crops, especially affecting small producers (Pérez and Pérez 2002; Dadhich and Meena 2014; Kumar et al. 2018).

Palm oil, which began to have important participation toward the end of the 1990s, has been increasing its participation to position itself in first place in terms of harvested area for 2016, with a participation of 21% nationwide. This is related to the fact that cultivation of African palm demands large areas of land, but it also responds to a strong government policy that has encouraged this type of cultivation: "As of 2001, within the framework of government policy of reactivation of the agricultural sector, the palm sector benefited from specific support such as lines of credit with a subsidized rate for new crops and incentives for capitalization" (Leibovich and Estrada 2008; Yadav et al. 2017; Kakraliya et al. 2018). In this socioeconomic context so far presented, it can be affirmed that in order to understand the relationship between land loss and the rural sector, it is pertinent to understand how the rural sector is structured in the country (since this leads to differential impacts of land loss) as well as the mechanisms of response to soil degradation processes.

In Colombia, the occupation of rural areas is not homogeneous. Many settlements mainly in the central zone of the country are scattered—characteristic particularly of the Andean zone—and more nucleated in some areas of the Caribbean region. Another element that makes Colombia a special case is the land tenure structure, characterized by latifundio, mainly cattle ranchers in the Caribbean region and small plots in the central and southern areas of the country. The characteristics of the population are also heterogeneous, since in the rural territory, there are economic groups linked to the land with large capital invested and also peasants who produce on small units of land or who are in processes of uprooting; likewise, there are indigenous communities, Afro-descendants, and the Raizal community. This heterogeneity in the structure and rural dynamics from the official perspective has been defined by the planning governing body in this way: "the rural world covers from relatively developed areas with a strong articulation, large and intermediate cities, to other extremely poor areas, generally in the most far-flung regions of the country" (National Planning Department DNP 2015).

Regarding the structure of land tenure, 36% of family production units have such access. However, it should be clarified that in many cases, as indicated in the document of the National Planning Department (2015), the land is owned but in insufficient quantities to maintain an adequate level of production that allows quality of life for its inhabitants. This characteristic determines to a large extent that many of the small productive plots are exploited intensively, accelerating soil degradation processes. The National Agricultural Census carried out in 2014 (Ministry of Agriculture-DANE 2016) found that 70.4% of APUs have less than 5 ha and occupy 2% of the dispersed rural area surveyed, while 0.2% have 1000 ha or more and occupy 73.8% of the dispersed rural area surveyed.

The same Ministry of Agriculture-DANE (2016) highlights that the departments with the highest number of APUs are Boyacá (339,888) and Nariño (254,569), corresponding to 25.1% of the number of units and occupying 4.8% of the dispersed rural area surveyed (5,265,559 ha). These departments are traditionally the seat of the peasant population. It is also highlighted that 34.5% (817,714) has land for agricultural use, and 56.6% is devoted to livestock uses, with 8.9% having natural forest cover.

The data presented allow us to explain that from a socioeconomic perspective, the tenure and productivity structure of rural areas are composed in the first instance, according to Forero (2003), of a capitalist agricultural enterprise, characterized by an industrial-type agriculture, mechanized and with technical assistance; in the second instance, of cattle ranching of speculative character; and, in third instance, of family production, which corresponds to the sector of the peasants, differentiated by the fact that the units of production and consumption are of family type, and their income is directly related to the work in agricultural tasks and other activities such as raising small animals, making handicrafts, and preparing food for sale in local markets..

9.6 Conclusion

It is thus possible to affirm that when lands are losing their productive potential the socioeconomic impact is differential according to this tenure structure, the possibility to diversify uses, and also the possibility of obtaining credits for productive projects. Therefore, the social and economic effects of the loss of land affect smallholders, small producers or family production units, peasants, and ethnic communities to a greater extent. In this socioeconomic context, an institutional budget is required that considers reference knowledge and other logics of reordering of the territories that enable economic growth with development, based on knowledge and management of territory that recognizes the current state of soils, their most suitable potentialities, and more appropriate uses that are economically and environmentally viable.

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Soil Microbes for Sustainable Agriculture

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Abstract

Soils are habitats for major forms of life such as microorganisms (e.g., bacteria, archaea, fungi) as well as insects, annelids, algae, and plants. Microorganisms have potential roles to play in sustainable agricultural production due to their ability to promote plant growth and enhance biotic and abiotic stress resistance, remediate contaminated soils, recycle nutrients, manage soil fertility, and weather and mineralize rocks and other abilities that result in the reduced use of fertilizers or pesticides in agriculture. Recently introduced biotechnological approaches help to modify microbes that can be used to enhance bioremediation and phytoremediation of contaminated soil that can be used for agricultural production. Sustainable agriculture is essential today to meet our long-term agricultural needs by using natural resources without degrading the environment. Here, we discuss the structure and diversity of soil microorganisms and their potential role in nutrient recycling, remediation of heavy metal from contaminated environments, plant growth promotion, stress tolerance, phytohormone production, etc. for sustainable agriculture to feed future generations.

Keywords

Heavy metal contamination · Nutrient recycling · Plant growth · Soil microbes

Abbreviations

DNA	Deoxyribonucleic acid
RNA	Ribonucleic acid
DPANN	Diapherotrites, Parvarchaeota, Aenigmarchaeota, Nanoarchaeota, Nanohaloarchaea
EM	Ectomycorrhiza
BNF	Biological nitrogen fixation
PSOs	Phosphorus-solubilizing organisms
PGPB	Plant growth-promoting bacteria
IAA	Indole-3-acetic acid
PIN	PIN-FORMED protein
GA3	Gibberellins
EPS	Exopolysaccharide

10.1 Introduction

Soils are heterogeneous habitats that support microbial populations of enormous size and diversity. Soils are home to a vast diversity of bacteria, archaea, fungi, insects, annelids, and other invertebrates as well as plants and algae. Soils provide food or nutrients to all organisms either living above or below the ground and also play critical roles in buffering and filtering freshwater ecosystem. Moreover, soil microbes such as bacteria, archaea, fungi, and cyanobacteria play diverse and often crucial roles in ecosystem services. The vast metabolic diversity of soil microbes means that their activities drive or contribute to the cycling of all major elements (e.g., C, N, P), and this cycling affects the structure and the functions of the soil ecosystem as well as the ability of soil to provide environmental services to people (Aislabie and Deslippe 2013; Meena et al. 2015d).

Agriculture faces the great challenge of providing food using limited natural resources to an ever-growing human population in the face of climate change. This great challenge cannot be faced without sustainable development (Altieri et al. 2017; Kumar et al. 2017b) that meets the needs of the present without compromising the ability of future generations to meet their own needs (ONU 1992). Sustainable agriculture is a set of strategies, especially management, which improve or maintain the quality and quantity of the food supply without compromising the environment or productivity of crops over the long term. Sustainable agriculture is essential today as it endeavors to meet our long-term agricultural needs by using specialized cultivation techniques that strive to fully utilize natural resources, something that conventional agriculture fails to achieve. This principle is environment-friendly and ensures safe and healthy agricultural products (Manzano-Agugliaro and Cañero 2010; Nuijten et al. 2016; Gázquez et al. 2016; Zapata-Sierra and Manzano-Agugliaro 2017; Yadav et al. 2018b). In sustainable agriculture, microorganisms have potential roles due to their ability to promote plant growth and stress resistance, remediate soil contaminated with heavy metals, recycle nutrients, manage soil fertility over long term, and promote the mineralization of rocks and their abilities to reduce fertilizers or pesticidal use in agriculture. The objective of this chapter is to discuss soil microbes, their function, and potential scope to use them in agricultural sustainability.

10.2 Soil Microbial Diversity

Although the size of an individual soil microorganism is very small, they have very significant effects on the physical, chemical, and biological processes in soil that are directly and indirectly critical for the growth and development of a plant and animal. Bacteria and archaea are single-celled organisms that often take the form of rods, cocci, or spirals, and a few may also form branching filaments, such as the actinomycetales. Bacterial DNA lies free within the cytoplasm since they do not have a membrane-bound nucleus. Their genome usually comprises a single circular chromosome and 2–7 smaller DNA elements known as plasmids. The genome size of bacteria is about 4000–6000 kbp and encodes 3000–4000 proteins. Bacteria usually have cell wall composed of a protein, carbohydrate, and lipid. Like other organisms, bacteria and archaea require carbon to synthesize the building blocks of the cell and require energy to drive the reactions involved in cell synthesis and metabolism. Some bacteria require oxygen to grow while other bacteria and many archaea use alternative electron acceptors, including nitrate and sulfate. For such type of anaerobic organisms' oxygen may be toxic. On the basis of energy requirement, microbes can be classified into two types: autotrophs or heterotrophs. Sunlight (photoautotrophs) and the oxidation of reduced inorganic compounds (e.g., Fe^{2+}, ammonia, or nitrite; chemoautotrophs) are the main sources of energy for autotrophic microbes to fix carbon dioxide to produce carbohydrate, fat, and protein, whereas heterotrophs use organic carbon compounds as a source of carbon and energy.

Archaea were known as extremophiles due to their abundance in harsh environments, but now it is found that they are ubiquitous in nature and widespread in many environments, including soil. Morphologically archaea and bacteria are similar, but phylogenetic analyses of 16S ribosomal RNA gene sequences revealed that the living organisms can be divided into three domains, with archaea being more closely related to eukaryotes than the bacteria (Woese et al. 1990).

Fungi, as eukaryotes, are more closely related to plant and animal than to bacteria or archaea. A membrane-bound nucleus with single or multiple chromosomes and membrane-bound organelles such as mitochondria are present in fungi. Glucans and chitin are the main components of the fungal cell wall. Fungi are heterotrophic organisms and their usual nutritional strategy is saprophytic, meaning that they feed on decaying matter. Fungi can be single-celled organisms known as yeast, while many grow in the form of a threadlike structure known as hyphae. These are commonly 2–10 μm in diameter and may be either septate or nonseptate.

Different factors like climate, vegetation, physical and chemical properties of the soil, crop cultivation, etc., influence the number of soil organisms, their diversity, biomass, and metabolic activity. For example, species diversity of soil microorganism differs totally between arid desert and humid forest, acid soils, and alkaline soils.

Initially, only cultivatable bacterial and fungal soil diversity was studied, but it represents less than 10% of the soil bacterial community. Thus, scientists were looking for other approaches. During the 1980s Norman Pace and his colleagues realized that naturally occurring microbes could be identified without culturing them (Hugenholtz et al. 1998). The extraction of DNA from soil to the amplification and sequencing of ribosomal RNA using appropriate primers followed by phylogenetic analysis helped to identify microbial species from soil. Thus, more diverse organisms could be studied by recently introduced molecular techniques. For example, sequencing of 16S rRNA and other housekeeping genes allows speculation about an organism's characteristic and identification of their closest cultivatable relative. Physiological properties of microbes can also be inferred from phylogenetic conclusions; for example, all cyanobacteria form a monophyletic group, as do many sulfate-reducing bacteria, halophiles, and methanogenic archaea (Aislabie and Deslippe 2013; Ashoka et al. 2017; Kakraliya et al. 2018).

10.2.1 Soil Bacterial Phyla

Amplification and sequencing of 16S rRNA genes from soil bacteria found at least 32 bacterium phylum-level groups, and the dominant phyla were *Proteobacteria*, *Acidobacteria*, *Actinobacteria*, *Verrucomicrobia*, *Bacteroidetes*, *Chloroflexi*, *Planctomycetes*, *Gemmatimonadetes*, and *Firmicutes*, which together represent an average of 92% of soil libraries (Janssen 2006). Although 52 bacterial phyla were described by Rappé and Giovannoni (2003), and 24 were recognized by Bergey's Manual (Garrity et al. 2004), soils seem to be dominated by only the abovementioned nine bacterial phyla. Interestingly, although the number of phyla in soil is low, species diversity is high compared with other environments (Nemergut et al. 2011; Meena and Meena 2017). *Proteobacteria* and *Acidobacteria* are the most abundant soil bacterial phyla. Different members of *Proteobacteria* make up an average of 39% of libraries derived from soil bacterial communities. The phylum *Proteobacteria* can is classified within the classes *α-Proteobacteria*, *β-Proteobacteria*, *γ-Proteobacteria*, and *δ-Proteobacteria* (Janssen 2006). Members of α, β, and γ subphyla are more prevalent in rhizosphere soils where nutrient availability is high (Fierer et al. 2007). The number of *β-* and *γ-Proteobacteria* in soil can be increased by adding low-molecular-weight carbon sources (Goldfarb et al. 2011; Eilers et al. 2012; Yadav et al. 2018a).

Agrobacterium, *Alcaligenes*, *Arthrobacter*, *Bacillus*, *Flavobacterium*, *Micromonospora*, *Nocardia*, *Pseudomonas*, and *Streptomyces* are the dominant bacterial genera in soil among the cultivatable species (Alexander 1977), but these nine genera together make up only 2.5–3.2% of soil bacteria. Of these, *Pseudomonas* spp. are the most abundant in soil bacterial communities, contributing 1.6% of the cloned sequences from soils (Janssen 2006; Meena and Yadav 2015).

Heterotrophic, autotrophic, and methanotrophic bacteria are found in *β-Proteobacteria*; important genera are *Burkholderia*, *Alcaligenes*, and *Acidovorax*. *Burkholderia* species might play important roles in soil by participation in carbon turnover, nitrogen fixation, plant growth promotion, mineral weathering, and live hyphae degradation (de Boer et al. 2004; Uroz et al. 2007; Kumar et al. 2018b). The ammonia oxidizer *Nitrosospira*, the iron oxidizer *Thiobacillus*, and the phototroph *Rhodocyclus* are important autotrophs in *β-Proteobacteria* in soil.

Heterotrophic, lithotrophic, and phototrophic bacteria are found in *γ-Proteobacteria* in the soil. *Pseudomonas* and *Xanthomonas* are the best-known heterotrophic genera in *γ-Proteobacteria*. *Pseudomonas* species can use a wide range of nutrients; most grow on more than 50 different substrates, a few even on over 100 substrates. Sugar, amino acid, fatty acid, alcohol, and hydrocarbon can be utilized by *Pseudomonas* species.

Other sulfate- and iron-reducing bacteria belong to the order *δ-Proteobacteria*. In soil, the sulfate reducer *Desulfovibrio* grows aerobically using lactate or ethanol as carbon source. The genus *Bdellovibrio*, a parasite of other bacteria, also belongs to the *δ-Proteobacteria*. *Helicobacter* and *Campylobacter* are genera of *ε-Proteobacteria* present in soil. Both genera are also present in the digestive tract of animals and could enter the soil with bodily waste.

Thirteen percent of soil bacterial communities belong to the phylum *Actinobacteria*, which contains three subclasses (*Actinobacteridae*, *Acidimicrobidae*, and *Rubrobacteridae*). Moreover, it also contains the subclasses *Rubrobacteridae* and *Acidimicrobidae* (Janssen 2006). *Acidobacteria* are diverse and widespread in soil, especially in acidic soil (Lauber et al. 2009). It is very challenging to cultivate *Acidobacteria* in the laboratory; thus very little is known about their metabolic capabilities. Microbes with Gram-positive cell walls belonging to the *Actinobacteria* and *Firmicutes* are abundant in soil culture collections.

Endospore-forming bacteria and lactic acid bacteria are the members of phylum *Firmicutes*. *Bacillus* and *Clostridium* are the best-known genera of endospore-forming bacteria in soil. *Bacillus* spp. can degrade many different carbon sources, including plant polysaccharides. Some species of *Bacillus* are known to be fermentative, while others fix nitrogen or are denitrifiers. The genus *Clostridium* is metabolically diverse and can ferment sugar, starch, pectin, and cellulose. *Bacillus* and other species of bacteria produce endospores for surviving long term in soil during dry periods. Lactic acid bacteria (e.g., *Lactobacillus*) are found in decaying plant materials and are often aerotolerant anaerobes.

Some members of the phyla *Gemmatimonadetes*, *Chloroflexi*, and *Planctomycetes* are poorly known because many are difficult to culture in the laboratory. Thus, their physiology, genetics, and ecology are also poorly understood. *Gemmatimonadetes* are aerobic heterotrophs that are adapted to low soil moisture conditions (de Bruyn et al. 2011; Varma et al. 2017). Aerobic heterotrophs that belong to the *Chloroflexi* can grow on oligotrophic media and can respire organohalide compounds (Davis et al. 2011).

10.2.2 Soil Archaeal Phyla

The archaea are one of the three primary domains of life (Woese et al. 1990). Archaea are unique in nature due to their presence in the environment with high temperature, extreme pH value, and saline conditions. Archaea a diverse domain of life, and members may exhibit small cells and genome and very low metabolic activity. Genome reduction plays a predominant role in archaeal evolution by which a small-genomed archaeal ancestor subsequently developed complexity via gene duplication and horizontal gene transfer (Williams et al. 2016; Dadhich and Meena 2014; Gogoi et al. 2018). Recent advances in traditional and molecular methods, used for diversity study, have opened a wide window on the diversity of archaea and have resulted in the description of economically important new lineages. Sequencing of 16S rRNA genes found 20 archaeal phyla in environmental samples, but 14 phyla do not have any known culturable representatives (Schloss et al. 2016). Described lineages of archaea are the Euryarchaeota, Thaumarchaeota, Aigarchaeota, Crenarchaeota, Korarchaeota, and DPANN (Diapherotrites, Parvarchaeota, Aenigmarchaeota, Nanoarchaeota, Nanohaloarchaea, and Asgard) (Brochier-Armanet et al. 2008; Guy and Ettema. 2011; Zaremba-Niedzwiedzka et al. 2017). Among these, Asgard is a sister group to TACK (Thaumarchaeota, Aigarchaeota, Crenarchaeota, Korarchaeota) and is considered more closely related to the original eukaryote.

Archaea are important for sustainable agriculture since they take part in ammonia oxidation and play critical roles in the global nitrogen cycle. Different members of archaea are involved in many steps of the nitrogen cycle, such as nitrate respiration and denitrification (Cabello et al. 2004; Meena et al. 2016a). Autotrophic and heterotrophic members of archaea catalyze iron and sulfur oxidation to enhance the release rate of metals and sulfur to the environment (Baker and Banfield 2003; Buragohain et al. 2017). All known methanogenic organisms belong exclusively to the archaeal domain and are generally found in oxygen-depleted environment. Archaea have a large influence in the nitrogen cycle, particularly ammonia oxidation, and the global methane cycle, but their involvement in plant phosphorus nutrition is very limited. Yadav et al. (2015) isolated twenty archaeal strains that were able to solubilize soil phosphorus. The strain IARI-WRAB2 was identified as the most efficient P-solubilizer (134.61 mg l^{-1}) followed by *Halococcus hamelinensis* strain IARI-SNS2 (112.56 mg l^{-1}). Isolated strains produced gluconic acid, citric acid, formic acid, fumaric acid, succinic acid, propionic acid, and tartaric acid to influence P availability.

10.2.3 Soil Fungal Phyla

Fungi are ancient microorganisms found in all ecological niches, including soil. Phylogenetic analysis of 192 proteins encoded by single to low-copy number genes from fungal samples suggested that there are seven phyla in the fungal kingdom. These are *Ascomycota*, *Basidiomycota*, *Blastocladiomycota*, *Cryptomycota*, *Chytridiomycota*, *Mucoromycota*, and *Zoopagomycota*. Phylogenetic analysis showed that the phylum *Cryptomycota* is the earliest diverging lineage of fungi, followed by the phyla *Chytridiomycota* and *Blastocladiomycota* (Spatafora et al. 2016). Moreover, it is assumed that there are 1.5 million to 5 million species of fungi present on Earth (Hibbett et al. 2007; Dadhich et al. 2015). *Chytridiomycota* are widely distributed and saprophytic in nature.

Rhizospheric soil influences the taxonomic and functional diversity of soil microbes, including fungi, because plant roots exude carbon compounds and excrete and adsorb nutrients from the rhizosphere. The fungal mycelium acts as a major route of carbon flow between the plant and the soil microbial community. About 1–22% of photosynthetic substances of plants are distributed to their ectomycorrhizal (EM) fungus partner (Hobbie 2006). The EM fungi release carbon from the hyphae as trehalose, mannitol, and oxalic acid. Nonetheless, mycorrhizal root tips and their vegetative mycelium also provide habitat for bacteria. Thus, fungi are important for the growth and development of plants.

10.2.4 Soil Algal Phyla

Soil algae may be unicellular or multicellular organisms, living both on the soil surface and within the soil. Most soil algae can be found growing on the soil surface or within the top millimeters of the soil. A typical abundance of algae in soil is about 10^6 cells per gram of soil. Indigenous soil algae can move from the surface to the subsurface of the soil horizon and may thus become allochthonous organisms. Algal genera known to inhabit the soil are *Chlorophycophyta*, *Euglenophycophyta*, *Rhodophycophyta*, and *Chrysophycophyta* (Aislabie and Deslippe 2013).

10.3 Nutrient Recycling and Soil Microbes

The chemical and physical recovery of substances for new use is known as recycling. Change in chemical form leading to the physical translocation of materials could also be defined as recycling. All living organisms influence their environment by chemical transformation, and oxidation and reduction by microbes is a major driver for the chemical transformation of different plant nutrients. Soil microbes play important roles in the recycling of many nutrients that are essential for life. Different nutrients like carbon, nitrogen, phosphorus, potassium, zinc, calcium, manganese, and silicon are continuously recycled by microbes. Nutrient recycling is essential because it provides the raw materials to produce amino acids, proteins, DNA, and RNA, which are the building blocks of all known forms of life. For example, weathering of minerals – the main mechanism for converting minerals to plant nutrients – is significantly influenced by microbes such as bacteria and fungi. Weathering is a process by which many plant nutrients are released from minerals. Different nutrients like calcium, magnesium, and potassium are released from weathering of silicate minerals while apatite weathering releases phosphorus in soil. Thus, mineral weathering by soil microbes plays a significant role in ion cycling and plant nutrition (Aislabie and Deslippe 2013; Meena and Yadav 2014).

10.3.1 Carbon Cycling

Carbon (C) is the key constituent of all living organisms and cycling of carbon is significantly regulated by microbes. Plants, cyanobacteria, and free-living and symbiotic lichens are primary producers and fix CO_2 to convert it to organic material. All organic materials are derived from primary producers. Autotrophic microbes can also fix CO_2 in soil. Nonliving organic materials are recycled by soilborne heterotrophic bacteria and fungi. These soil saprotrophs complete the carbon cycle by converting organic material to CO_2 during respiration. In many cases, higher animals (herbivores and carnivores) also need microbes residing in their intestinal tracts to digest particulate organic materials. The degradation of nonliving organic material to carbon dioxide is known as decomposition and is essential to obtain energy for growth. Nonetheless, mineralization of the organic compounds occurs when they are completely degraded into inorganic materials such as CO_2, ammonia, and water (Aislabie and Deslippe 2013; Layek et al. 2018).

The major agents of organic matter decomposition are fungi and bacteria, and they can also degrade complex organic molecules from the environment. Organic molecules such as organic acid, amino acid, and sugar are degraded by bacteria, especially by *Actinobacteria* and *Proteobacteria* (Eilers et al. 2012; Verma et al. 2015b). *Bacteroidetes* of bacteria help to degrade more complex carbon compound such as cellulose, lignin, and chitin, although they need relatively high amounts of available nitrogen to support the production of extracellular and transport enzymes (Treseder et al. 2011). In contrast, bacteria from low N environments are more efficient at metabolizing organic N compounds such as amino acids. Carbon mineralization in soils is positively correlated with abundance of *β-Proteobacteria* and *Bacteroidetes* while negatively correlated with *Acidobacteria* abundance (Fierer et al. 2007).

Degradation of organic matter under anaerobic conditions is only carried out by microbes who produce organic acids and gases such as hydrogen and carbon dioxide from organic compounds. Under strictly anaerobic conditions methanogenic bacteria use hydrogen to reduce the CO_2 and to produce CH_4 gas. Moreover, methanogenic bacteria can metabolize methanol, acetate, or methylamine to CH_4 and CO_2 (Aislabie and Deslippe 2013; Kumar et al. 2018a).

10.3.2 Nitrogen Cycling

Nitrogen (N) is an essential element for all living organism as it is a main constituent of protein and nucleic acids. Protein and nucleic acids are the building blocks of all living systems. Although animals obtain N from organic sources, plants get N from inorganic nitrogen sources such as ammonium and nitrate or simple amino acids (e.g., glycine). Different N pathways such as nitrogen fixation, dissimilatory nitrate reduction to ammonia (DNRA), nitrification, ammonification, and denitrification are employed by microbes. Different microbial processes of N pathways often limit ecosystem productivity as plant biomass production is significantly influenced by N (Aislabie and Deslippe 2013; Meena et al. 2018c).

Biological nitrogen fixation (BNF), the reduction of atmospheric free nitrogen gas to ammonium, is only carried out by prokaryotes. Nitrogen fixation is the only biological process through which new N enters into the biosphere, so it is critically important for ecosystem function. The ammonium produced during BNF is assimilated into amino acids and subsequently polymerized into proteins. Nitrogen-limiting conditions in soil induce nitrogen fixation by microbes. Although rhizobia (*Rhizobium*, *Mesorhizobium*) and *Frankia* are the main players for symbiotic BNF, nitrogen fixation is also carried out by free-living microbes (e.g., *Azotobacter*, *Azospirillum*, *Burkholderia*, *Clostridium*, and some methanogens). Root exudates from plants may supply some of the energy required for nitrogen fixation. Nitrogen fixation rates through symbiotic process are often two or three times higher than those of free-living soil bacteria.

Nitrification is another important process for the availability of plant N in which ammonia or ammonium ions are oxidized to nitrite and then to nitrate. The whole process of nitrification is strictly dependent on a few autotrophic bacteria and Crenarchaeota. Oxidation of ammonia to nitrite is mediated by bacteria like *Nitrosospira* and *Nitrosomonas* or the *crenarchaeum Nitrososphaera*, whereas the oxidation of nitrite to nitrate is mediated by bacteria such as *Nitrobacter* and *Nitrospira*. Nitrification also has some agricultural disadvantages because the oxidation of ammonium to nitrite changes its charge from positive to negative. This leads to nitrate leaching as the negatively charged ions do not interact strongly with soil particulates and can be readily washed into groundwater, which is an important factor for groundwater contamination.

Denitrification is a microbial respiratory process during which soluble nitrogen oxides are used as alternative electron acceptors under anaerobic conditions. Nitrate (NO_3^-), nitrite (NO_2^-), and nitric oxide (NO) are converted to greenhouse gas (GHG), i.e., nitrous oxide (N_2O) or nitrogen gas (N_2). It occurs predominantly in waterlogged soil that has become anaerobic. Complete denitrification (N_2 production) is the major biological mechanism by which fixed N returns to the atmosphere from soil and water and completes the nitrogen cycle. Denitrification creates considerable losses of fixed N from soil, thus limiting the availability of nitrogen essential for crop production. Denitrification is carried out by a diverse range of phylogenetically unrelated soil bacteria (*Proteobacteria*, *Actinobacteria*, and *Firmicutes*), fungi, and other soil eukaryotes. Many denitrifying organisms lack one or more of the enzymes involved in denitrification and are known as "incomplete" denitrifiers. For example, most fungi and approximately one-third of sequenced bacterial denitrifiers (Kobayashi et al. 1996; Philippot et al. 2011; Meena et al. 2018a) lack N_2O reductase enzymes, so their final denitrification product is N_2O. This incomplete denitrification product is a major source of GHG emissions from pastoral agriculture in New Zealand (Saggar et al. 2012). Multiple steps in the nitrogen cycle are influenced by bacteria. For example, *Rhizobium*, *Bradyrhizobium*, and *Azospirillum* have members that both fix nitrogen and denitrify. Nitrifying bacteria such as *Nitrosomonas* can also participate in denitrification.

Nelson et al. (2016) used soil metagenomic data to characterize the biogeography of microbial nitrogen metabolism traits and concluded that about 402 bacterial and 53 archaeal genera encoded nitrogen pathways. Similar trends are also found in bacteria and archaea for their relative frequency of N pathways, except for the dissimilatory nitrite reduction to ammonium pathway (DNRA), which is absent in archaea. Fungal sequences are only associated with assimilatory pathways, including ammonia assimilation, assimilatory nitrate to nitrite, and assimilatory nitrite to ammonium.

10.3.3 Phosphorus Cycling

Phosphorus (P) is not an abundant element in the environment and normally occurs as phosphate in organic and inorganic compounds. Phosphorus availability is reduced at neutral and alkaline pH due to their tendency to precipitate in the presence of divalent and trivalent cations. Microorganisms play an important role in P recycling. Physical movement of P occurs in the P cycle without alteration of the oxidation state. Microorganisms do not usually oxidize or reduce P but assimilate inorganic phosphate and mineralize organic P compounds. In many cases, P is combined with calcium, making them insoluble and unavailable for plants.

Microbes mineralize organic P to form inorganic phosphate by phosphatase enzymes produced by many bacteria and fungi. Moreover, microbes transform insoluble and immobilized inorganic P to soluble or mobile P by producing organic acids. Microbes release P not only for their own use but also for plants and other soil organisms. Mycorrhizal fungi produce oxalate to release phosphate from insoluble mineral P, which is a major strategy for enhancing P availability, allowing plants to overcome P deficiency. Several ectomycorrhizal basidiomycetous fungi have high-affinity phosphate transporters that are expressed in extraradical hyphae in response to phosphorus deficiency in their host (Plassard and Dell 2010; Meena et al. 2015e).

By polymerization, orthophosphate molecules can be linked with each other by phosphoanhydride bonds to make polyphosphate. Polyphosphate (poly-P) is an important compound for organisms to grow for longer period under adverse conditions (Mukherjee et al. 2015). Microorganisms like cyanobacteria and microalgae take up inorganic phosphorus from their growing environment and store it within their cells as poly-P granules to adapt to unfavorable conditions like salt stress, osmotic stress, UV radiation, and fluctuations of pH and temperature in the environment (Achbergerová and Nahalka 2011).

Different microalgal species like *Chlorella* sp. and *Scenedesmus* sp. and cyanobacterial species like *Aphanothece* sp., *Spirulina* sp., *Arthrospira* sp., and *Phormidium* sp. are being used in bioremediation for the removal of nutrients from wastewater (Ray et al. 2013). These microalgae and cyanobacteria could not only be used for excess P removal from wastewater and other polluted environments, but the poly-P in their cells could also be utilized in soil as slow and moderate release phosphorus as bio-fertilizers to optimize plant growth (Mukherjee et al. 2015; Datta et al. 2017b).

Moreover, the release of plant-available phosphorus from the insoluble poly-P present in the biomass of microalgae and cyanobacteria is influenced by the activity of phosphorus-solubilizing organisms (PSOs) in the soil, making the whole process very slow and steady, and thus P supply in the rhizosphere occurs according to the demand of crops. This process therefore reduces the probability of excess P supply (Ray et al. 2013) and control the loss of inorganic phosphorus as soil runoff originating from the injudicious use of inorganic fertilizers.

10.3.4 Sulfur Cycling

Sulfur (S) is present in various organic and inorganic compounds that are transformed from an oxidized state (SO_4^-) to a reduced state (H_2S) by different microorganisms. The S cycle cannot be completed without the help of microorganisms. Both sulfate and hydrogen sulfides are produced from the removal of sulfur from organic compounds under aerobic and anaerobic conditions. In both cases, bacteria play important roles. Moreover, elemental S can be produced by sulfate-reducing bacteria (Atlas 1997).

10.3.5 Iron Cycling

Iron (Fe) cycling is very important for its availability to different organisms. The cycling of Fe is completed by microorganisms by transformation of ferrous (Fe^{2+}) and ferric (Fe^{3+}) oxidation states. The ferric states are less soluble in water; hence plants cannot use Fe in this form. Thus, the conversion of the ferric state to the ferrous state by microorganisms, especially by bacteria, is very important for agricultural sustainability. Different bacterial genera such as *Thiobacillus*, *Galionella*, and *Leptothrix* oxidize iron compounds and enhance plant nutrition. A few species of these genera can deposit ferric hydroxide on their extracellular sheath. Over billions of years, this deposition can form substantial Fe deposits (Atlas 1997).

10.3.6 Calcium Cycling

Calcium (Ca) bicarbonate and calcium carbonate are two forms of calcium in nature. The bicarbonate form is readily available for plants, but carbonate is not. Different acidic compounds produced by microorganisms solubilize, precipitate, and immobilize Ca compounds that are very important for plant growth and development. Different algal genera play an important role in the precipitation of calcium as calcium carbonate in marine habitats (Atlas 1997), which is an important source of Ca.

10.3.7 Silicon Cycling

Silicon-rich shell structures are found in many algae, especially in diatoms. Algae accumulate and precipitate silicon dioxide to form their outer shells. An enormous amount, about 10 billion metric tons, of silicon dioxide is precipitated in the oceans each year by different microorganisms. After death, the shells of these microorganisms develop into deposits of silicon dioxide. Various industries mine these deposits for silicon (Atlas 1997).

10.3.8 Manganese Cycling

Manganese (Mn) is mainly found in two forms: divalent manganese, which is water soluble, and the almost insoluble tetravalent manganic ion. Manganese oxides form from manganese ions by oxidation and form nodule-like structures on bacterial sheath under aerobic conditions. Mass growth of these types of bacteria such as *Leptothrix discophora* in ocean sediments is considered a major source of Mn (Atlas 1997).

10.4 Microbes for Remediation of Heavy Metal Contamination

Industrialization and modern agricultural practices are putting increasing negative pressure on agricultural soil and water by releasing large quantities of hazardous waste, heavy metals, and organic contaminants that are a serious problem not only for agriculture but also for human health. Trace amount of different heavy metals like lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), zinc (Zn), uranium (Ur), selenium (Se), silver (Ag), gold (Au), nickel (Ni), and arsenic (As) is useful for plants, but upon excess uptake they reduce plant growth by imposing negative effects on plant photosynthesis, plant mineral nutrition, and the activities of essential enzymes (Gadd 2010; Yadav et al. 2017c). The presence of high concentrations of heavy metals in soil enhances absorption and accumulation of heavy metals by plant that enter the human body through the food chain (Sadon et al. 2012; Meena et al. 2015c). Metals in soil can be classified into five major geochemical forms: (i) exchangeable, (ii) bound as carbonates, (iii) bound as Fe and Mn oxides, (iv) bound to organic matter, and (v) residual metal. Microbes play an important role for the remediation of contaminated soils and are thus an important avenue for sustainable agriculture.

10.4.1 Sources of Heavy Metals

Pedogenetic processes of weathering of parent materials and anthropogenic sources are the main source of heavy metals in the environment, although the most significant natural sources are weathering of minerals, erosion, and volcanic activity. The anthropogenic source depends upon human activities such as mining, smelting, electroplating, pesticide and phosphate fertilizer discharge, application of biosolids (e.g., livestock manures, composts, and municipal sewage sludge), and atmospheric deposition (Dixit et al. 2015 and references therein). However, modern agricultural practices such as nonjudicial use of agrochemicals (pesticides, fertilizers, etc.), long-term application of urban sewage sludge, disposal of industrial waste, waste incineration, and vehicle exhaust are the main sources of heavy metals in agricultural soil.

10.4.2 Dominating Microbial Populations in Heavy Metal-Contaminated Soil

Soil is the major sink for heavy metal contamination, and one kilogram of soil can contain 1 to 100,000 mg of heavy metal (Gadd 2010). Soil microbes, especially rhizospheric microorganisms, play an important role for heavy metal detoxification in contaminated soil. Heavy metal detoxification in the rhizosphere occurs by a range of microorganism including prokaryotes and eukaryotes. Bacterial population structure in heavy metal-contaminated soil was studied by Pires et al. (2017), who concluded that *Firmicutes*, *Proteobacteria*, and *Actinobacteria* are dominating in soil and that the dominant genera were *Bacillus*, *Pseudomonas*, and *Arthrobacter*. Nodule formation and nitrogenase activity of rhizobia are sensitive to heavy metal. Symbiotically effective and heavy metal-tolerant rhizobial strains were found in contaminated soil and improve the quality of contaminated soil (Checcucci et al. 2017; Dhakal et al. 2015). Though *Ascomycota* and *Basidiomycota* are the predominant fungi in heavy metal-contaminated soil, arbuscular mycorrhizal fungi are dominant in nutrient-poor heavy metal-contaminated soil. A list of microbes involved in heavy metal remediation is given in Table 10.1.

Table 10.1 List of microorganisms involved in remediation of heavy metals from contaminated soil

Microorganism	Strain	Functions	References
Bacteria	*Achromobacter* sp. AO22	Volatilizes Hg^{2+} by *MerA* reductase to Hg^0	Kiyono and Pan-Hou (2006), Ng et al. (2009)
	Bacillus subtilis	Removes ferrous (Fe) by active bioaccumulation involving displacement of other ions Generates enzymes to bind metals into less harmful complexes that are stored within the cell	Holan et al. (1994)
	Bacillus licheniformis	Removes metals (Cd, Cr) by bioaccumulation	Zouboulis et al. (2004)
	Deinococcus radiodurans	Removes heavy metals through transformation	Brim et al. (2000)
	Desulfovibrio desulfuricans	Removes metals (Cu, Cr, Ni) by physical adsorption and metabolic processes	Kim et al. (2015)
	Escherichia coli	Expresses different proteins and peptides and activates different molecular mechanisms for the remediation of Zn, Cu, As, Cd, and Hg from soil	Murtaza et al. (2002), Kostal et al. (2004), Kang et al. (2007)
	Enterobacter cloacae	Bioremediation of heavy metals (Pb, Cd, Ni) occurs by antioxidant enzyme activity, flocculant production, and protein expression	Kang et al. (2015)
	Klebsiella pneumonia M426	Volatilizes Hg (II) to Hg (0) by a reductase enzyme and removes mercury as insoluble Hg through the formation of volatile thiols	Essa et al. (2002)
	Kocuria rhizophila	Remove metals by adsorption (Cd, Cr)	Haq et al. (2016)
	Micrococcus luteus	Cells are able to absorb metals (Cu, Pb), probably by passive physical mechanisms involving cell walls as well as cytoplasmic mechanisms	Puyen et al. (2012)
	Pseudomonas fluorescens	The biosorption of nickel ions (Ni) occurs in free cells or immobilized cells Produces low-molecular-weight cystine-rich proteins called metallothioneins for removing Hg and Cr from contaminated soils	Lopez et al. (2002), Gupta and Diwan (2017)
	Sulfate-reducing bacteria	Biosorption of arsenic occurs in free or immobilized cells	Teclu et al. (2008)

(continued)

Table 10.1 (continued)

Microorganism	Strain	Functions	References
Fungi			
	Aspergillus niger	Capable of accumulating heavy metals (Au, Cu) within their structure	Dursun et al. (2003)
	Botrytis cinereus	Pb (II) ions accumulated by biosorption	Akar et al. (2005)
	Penicillium chrysogenum; Penicillium spinulosum	Remove metals (Zn, Pb) by biosorption	Nemec et al. (1977), Tobin et al. (1984), Townsley et al. (1986), Niu et al. (1993)
	Phanerochaete chrysosporium	Removes metals (Pb, Cu, Zn) by biosorption	Iqbal and Edyvean (2004)
	Pleurotus platypus	Removes metals (Pb) by biosorption	Das et al. (2010)
	Rhizopus arrhizus	Take up heavy metals (Ag, Hg, Zn, Cd, Pb) using electrostatic attraction to charged functional groups	Tobin et al. (1984)
	Rhizopus oryzae	Removes Cu by adsorption	Fu et al. (2012)
	Saccharomyces cerevisiae	Heavy metals [Zn (II) and Cd (II)] removed through an ion exchange mechanism	Chen and Wang (2007), Talos et al. (2009)
Algae/ cyanobacteria	*Asparagopsis armata*	Removes metals (Cd, Ni, Zn, Cu) by biosorption	Yang et al. (2015)
	Codium vermilara	Removes metals (Cd, Ni, Zn, Cu, and Pb) by biosorption	Yang et al. (2015)
	Lessonia nigrescens	Adsorption of metals by electrostatic interaction	Hansen et al. (2006)
	Sargassum muticum	Used as biosorbent for Sb	Ungureanu et al. (2015)
	Spirogyra spp.	Binding of heavy metal (Pb) onto the cell surface and to cytoplasmic ligands, phytochelatins, metallothioneins, and other intracellular molecules	Gupta and Rastogi (2008)
	Spirulina spp.	Remove heavy metals (Cr, Cu, Mn, and Zn) by adsorption, phytosorption, and affinity to negatively charged cell wall components	Mane and Bhosle (2012), Coelho et al. (2015)

10.4.3 Microbial Mechanisms for Heavy Metal Tolerance

Some traditional/conventional techniques such as adsorption processes, chemical oxidation/reduction, reverse osmosis, and sludge filtration have been used for the removal of heavy metals from the environment. However, they have some limitations like high reagent requirement, and in a few cases these methods are not sensitive enough to recover the heavy metal ions, which may behave unpredictably. Bioremediation is an avenue for the removal of heavy metal ions from polluted environment using the activities of algae, bacteria, fungi, or plants. Bioremediation using microorganisms is sustainable because they help to restore the natural state of the polluted environment with long-term environmental benefit and cost-effectiveness.

Detoxification of heavy metals by microorganisms can occur naturally or through the addition of electron acceptors, nutrients, or other factors. Microorganisms use several techniques (Fig. 10.1) for heavy metal detoxification, such as biosorption, adsorption, and compartmentalization of heavy metals into intracellular molecules. Metal binding, vacuolar compartmentalization, and volatilization are important strategies that microorganisms use to detoxify heavy metals.

The valence transformation of heavy metals is a key mechanism for detoxification, especially for those metals whose toxicity depends on valence state. For example, mercury-resistant bacteria use organomercurial lyase to convert methyl mercury to Hg (II), which is one hundred times less toxic than methyl mercury (Wu et al. 2010; Meena et al. 2016b). Chromium-resistant bacteria convert Cr (VI) to Cr (II), which is less toxic and less mobile. Metal binding is another important mechanism of microbes that occurs through different chelators such as metallothioneins, phytochelatins, and metal-binding peptides. Chelators bind to the metal to facilitate microbial absorption and transport of metal ions.

Microorganisms can remove volatile heavy metals from contaminated environment. Heavy metals like mercury (Hg) and selenium (Se), which have volatile state, can be volatilized by microorganisms. By using the *MerA* enzyme, mercury-resistant bacteria reduce Hg^{2+} to the volatile elemental form Hg (0). Se (V) is also reduced to elemental Se (0) to remediate the contaminated environment (Wu et al. 2010). Microorganisms employ biosorption, bioaccumulation, biotransformation, and biomineralization to survive in the metal-polluted environment (Gadd 2000; Lin and Lin 2005; Varma et al. 2017a). Adsorption means the physical binding of ions and molecules onto a surface. Microorganisms carry different functional groups, like –SH, –OH, and –COOH, on their cell surface that absorbs metals from the polluted environment. Microbes also secrete chelating agents or disrupt particular transporter system to reduce metal ion accumulation in the cell. They also bind metal ions intracellularly to molecules such as thionein and change the distribution pattern of metal ions in the vacuole and mitochondria (Siddiquee et al. 2015; Yadav et al. 2017a).

In brief, microorganisms use cell wall-associated binding, intracellular accumulation, metal chelators, extracellular polymeric reactions with transformation, extracellular mobilization or immobilization of metal ions, and volatilization of metal

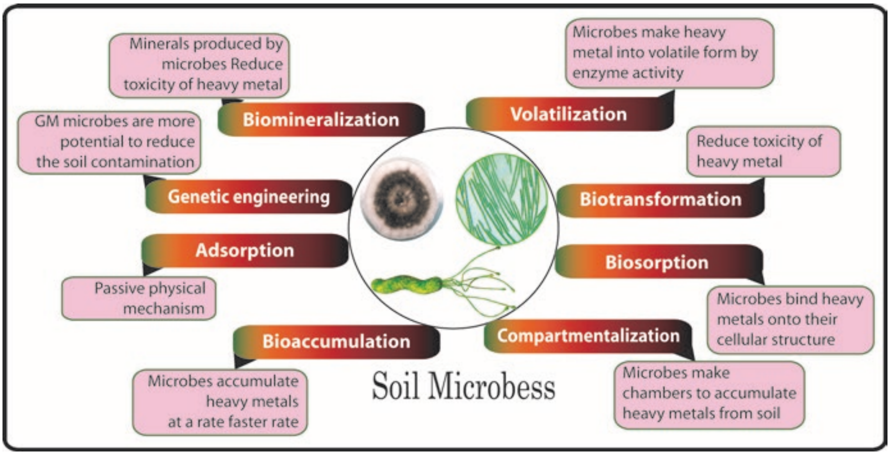

Fig. 10.1 Mechanisms of soil microbes for heavy metal detoxification from contaminated environments

ions to reduce the active concentration of metal ions present in the polluted environment. The high load of heavy metals in nutrient-poor soil is not a problem for arbuscular mycorrhizal fungi and other microbes because they bind metal ions on their external cell surface or transport them into the cells for compartmentalization (Ehrlich 1997).

Metal speciation, toxicity, mobility, dissolution, and deterioration are significantly influenced by microbes (Gadd 2010). Interaction of metals and microbes is a complex phenomenon that depends on physicochemical properties of the soil, type and concentration of metal species, metabolic activity of microbes, and the diversity of microbes. Behaviors of soil metals like for its mobility, biological activity, availability, and chemical nature are dependent on the ability of metals to react with organic compounds such as low-molecular-weight organic acid, carbohydrate, and enzyme secreted by microorganism (Patel et al. 2008; Meena et al. 2015a). However, bioavailability and accumulation of heavy metals are heavily influenced by the type and texture of soil, the physicochemical properties of the soil, plant genotype, and soil-plant-microbe interaction as well as agronomic practices such as fertilizer application, water management, and crop rotation system.

10.4.4 Microorganisms Use Heavy Metal for Their Own Growth and Development

Metals like Cu, Zn, Co, and Fe are essential for survival and growth of microbes, but the same metals also exhibit toxicity at higher concentration and may inactivate protein molecules (Oorts et al. 2006; Samanovic et al. 2012; Meena and Lal 2018). Although no biological function was observed for Al, Cd, and Hg, upon accumulation in microbial cell they may affect enzyme selectivity, interfere with cellular function, damage DNA structure, and may result in cell death (Belyaeva et al. 2012).

Nickel (Ni) is not only a primary nutrient for microbes but also plays essential roles in many microbial cellular processes. When Ni enters into the cell, it incorporated into several microbial enzymes like urease, NiFe hydrogenase, acetyl-CoA decarbonylases/synthase, methyl coenzyme Ni reductase, etc. (Mulrooney and Hausinger 2003), but Ni is toxic to bacteria at higher concentration. Therefore, different species of bacteria have developed different strategies to regulate the level of intracellular Ni to overcome this problem. For instance, *Bradyrhizobium japonicum HypB* has been shown to be able to bind up to 18 Ni ions per dimer and exhibits GTPase activity (Fu et al. 1995; Eitinger and Mandrand-Berthelot 2000; Mulrooney and Hausinger 2003). The Cu, Mo, and Mn ions bound predominantly with Fe to siderophores, resulting in an 84- to 100-fold increase in siderophore production (Balogh et al. 2003; Bellenger et al. 2007). Cobalt (Co) is essential for a broad range of physiological and biochemical functions of microbes (Jayakumar et al. 2008; Okamoto and Eltis 2011). For example, nodulation and nitrogen fixation in soybean has been found increased when Co is applied (Das et al. 2000; Meena et al. 2014). Moreover, rhizobial inoculation along with Co application significantly increased the total uptake of N, P, K, and Co by summer groundnut (Almeida et al. 2007; Kumar et al. 2017a).

10.5 Genetic Modification of Microorganisms for Sustainable Agriculture

The zone of soil around roots that is influenced by root activity is known as the rhizosphere. The intimacy of this interface between plants and their environment is essential for the acquisition of water and nutrient and for beneficial interaction with soilborne microorganism but also increases the vulnerability of plant to a range of biotic and abiotic stresses. Plant growth-promoting bacteria (PGPB), commonly known as rhizobacteria, have been engineered to enhance the production of stress-induced hormones, antibiotics, antifreeze proteins, trehalose, and lytic enzymes for enhancing plant growth and stress tolerance. Introduced PGPR must be established and maintain biologically active population for their success in competition with the already-adapted indigenous microbes. Genes involved in growth promotion have proven effective for strain improvement. Thus, attempts have been made to modify the timing or level of their expression or by transferring and expressing them in alternate hosts for enhancing plant growth and development (Ryan et al. 2009; Ram and Meena 2014).

10.5.1 Genetically Modified Microbes Enhance Plant Growth and Stress Tolerance

A number of attempts have been made to overexpress plant chitinase for enhancing plant protection against pathogenic fungi. Many researchers have reported that these approaches achieve tolerance in plants to different stresses, which along with increased crop yield is a major goal for sustainable agriculture. The endo-chitinases *CHIT33* and *CHIT42* from mycoparasite fungi were introduced into tobacco plants. Genetically modified tobacco plants expressing fungal *CHIT33* and *CHIT42* were resistant not only to a wide range of fungal and bacterial pathogens but also to biotic stresses such as salinity and heavy metal stress (Dana et al. 2006). Genetic modification of *E. coli* by the expression of the *chiA* gene caused rapid and extensive bursting of the hyphal tip of *Sclerotium rolfsii* and effectively reduced its ability to cause disease in beans (Shapira et al. 1989). Genetically modified *Pseudomonas* sp. containing and expressing the *chiA* gene from *Serratia marcescens* effectively controlled *Fusarium oxysporum* and *Gaeumannomyces graminis* (Sundheim et al. 1988). *Pseudomonas fluorescens* strain BL915 was modified by Ligon et al. (2000) to enhance the production of the antifungal compound pyrrolnitrin by introducing the *gacA* gene, and it was found that the synthesis of pyrrolnitrin in the modified strain of *Pseudomonas* constitutively expressed from a multicopy plasmid produced about 2.5-fold more pyrrolnitrin than the parental strain.

Pretreatment of the soil with the engineered strain effectively decontaminates the soil and reduces disease incidence (Timms-Wilson et al. 2000). An engineered derivative of *P. fluorescens* strain 5-2/4 expressing an integrated cassette carrying the DAPG biosynthesis operon showed increased control of *P. ultimum* (Alsanius et al. 2002). Recombinant bacterial strains (EG2424 and EG2348) were developed to enhance the efficiency of a biopesticide. The modified EG2424 strain was developed by conjugation of *Bacillus thuringiensis* strain *kurstaki* and *B. thuringiensis* strain *tenebrionis*, which were more active against European corn borer, Colorado potato beetle, and *Leptinotarsa decemlineata* (Sanahuja et al. 2011 and references therein). To extend the *B. thuringiensis* host range and efficiency, Wang et al. (2008) constructed a new strain by introducing the *cry3Aa7* gene into the UV17 strain, which produces *Cry1Aa*, *Cry1Ac*, *Cry1Ca*, and *Cry2Ab*. The new strain was toxic to both Lepidoptera and Coleoptera insects. Moreover, Liu et al. (2010) reported the construction of strain BIOT185 from the original strains HBF-1 and BTO 185 that express *Cry8ca2* and *Cry8Ea1*. The new strain is toxic toward scarab insect such as *Anomala corpulenta*.

10.5.2 Genetic Modification of Microbes for Enhancing Heavy Metal Remediation from Contaminated Environments

Microorganisms are modified by genetic engineering approaches for enhancing specific characteristics, such as enhancing the ability to degrade a wide range of contaminants for the bioremediation of soil, water, and activated sludge. Modified strains can survive and remain active in the environment. Plant-associated degradation of pollutants in soil by genetic modification of endophytic and rhizospheric bacteria is an important avenue for the remediation of contaminated soil (Dixit et al. 2015 and references therein). Therefore, modified strains can be used as bioremediators for the reclamation of polluted soil and water. Additionally, microbial biosensors have been designed to quantify the degree of contamination at the contaminated site quickly and accurately. A number of biosensors for determining the concentration of Hg, Ni, Cu, and As have been developed. Strains of *E. coli* and *Moraxella* sp. have been modified to enhance chelation on the cell surface and showed 25 times more accumulation of Cd and Hg compared to a wild-type strain (Bae et al. 2001, 2003; Meena et al. 2017a). The environmental plasmid *pTP6* (containing *merR1TPAGB1* and *merR2B2D2E* gene clusters) was introduced into *Cupriavidus metallidurans* strain MSR33; this modification enhanced Hg biodegradation with the synthesis of organomercurial compounds. *Deinococcus radiodurans* bacterial strain with chromium-reducing ability has been modified to enhance toluene degradation by transferring the *tod* and *xyl* operons of *P. putida* into them. The transgenic approach has been used to introduce the trehalose biosynthetic gene(s) into plants or into plant growth-promoting bacteria, but it has been much simpler to use genetically manipulated PGPB to achieve the same end because a single engineered bacterial strain may effectively protect a large number of different crop plants (Glick 2012 and references therein).

10.5.3 Biosensor Development and Genetic Modification of Microbes

Biosensors are analytical devices which are used to convert change in biological reaction into an electrical signal output and are made of a combination of a biological component, transducer, and electronic reader. It may use the concept of a general microbial bioassay, based upon estimation of the reduction in light transmittance (Rubban et al. 2015; Yadav et al. 2017b). Bacterial luminescence properties are also used in the biosensor development. For example, the bioluminescent bacterium *Vibrio fischeri* has been used to develop biosensors (Belkin 2006). Genetically modified *E. coli* strain Hb101 containing the *luxCDABE* gene cluster and the cyanobacterium *Synechocystis* PCC6803 carrying the *luc* gene from the firefly *Photinus pyralis* were also used to develop biosensors (Belkin 2006).

Genetically modified microbial biosensors were used for metal pollutant detection. For example, the *zra*P and *cus*C promoters of *E. coli* XL1 fused with *rfp* and *gfp* reporter genes were used to detect Cu and Zn at 5.10 mg l^{-1} and 2.59 mg l^{-1}, respectively (Ravikumar et al. 2012). *E. coli* modified by the introduction of the *merR* and *luxCDABE* genes was able to detect mercury (II) at a concentration of 1 μg l^{-1} (Ivask et al. 2007) and 3×10^{-3}μg l^{-1} (Ivask et al. 2009). The specificity of genetically modified microbial biosensors is very high for certain group of metals. For example, a genetically modified *Ralstonia eutropha* strain AE2515 was developed (Tibazarwa et al. 2001) by introducing the *cnrYXH* regulatory genes in the upstream region of *luxCDABE* for detecting Ni and Co. This biosensor worked very well for detecting Ni and Co but failed to detect Zn, Cr (III and V), Mn, Cd (II), and Cu (II) ions.

10.5.4 Genetically Modified Microbes for the Remediation of Organic Xenobiotic Contaminated Soil

Genetically engineered microbes are used to the transformation of organic xenobiotics to overcome the limitations of traditional methods of bioremediation. Genetic engineering techniques were used by different companies and academia during the 1990s to exploit microbial metabolism for the bioremediation of xenobiotics (Zwillich 2000), but they were hampered due to regulatory challenges involved in genetic engineering research. However, increased degradation of 3,4-chlorotoluene and 3-chlorotoluene was observed by Abril et al. (1989) and Brinkmann and Reineke (1992) in genetically modified *Pseudomonas* sp. Although the radiation-tolerant genetically modified microbe *Deinococcus radiodurans* was developed for toluene degradation, it was not used for bioremediation purpose in the field due to potential risks and regulatory challenges (Lang and Wullbrandt 1999; Ezezika and Singer 2010; Mitran et al. 2018).

With the advent of the latest biotechnological techniques such as genetic modification of bacterial strains using natural gene transfer, recombinant DNA technologies can be used to produce specific enzymes that promote the degradation of toxic organic substances (Chakraborty and Das 2016; Pandotra et al. 2018; Meena et al. 2017b). Moreover, the application of genetic engineering approaches to plant-associated endophytic and rhizospheric bacteria can enhance the degradation of toxic compounds in the contaminated site by phytoremediation (Fasani et al. 2017). Enzymes found in four *Pseudomonas* strains clearly showed oil biodegradation capabilities (Gao et al. 2017; Chebbi et al. 2017).

Agent Orange, one of the toxic herbicides and defoliants used in Vietnam War by the US military, is a mixture of phenyl herbicide including 2,4-dichlorophenoxyacetic acid (2,4-D) and 2,4,5-trichlorophenoxyacetic acid (2,4,5-T) and is closely linked to increased incidence of cancer (Ezezika and Singer 2010). A recombinant strain of *Burkholderia cepacia* was shown to be very effective for the degradation of Agent Orange (Chauhan et al. 2008). In artificially contaminated soil, the genetically modified endophytic *P. putida* strain VM1441 (pNAH7) increased naphthalene degradation rates up to 40% compared to uninoculated plants and protected pea plants against the toxic effect of naphthalene (Germaine et al. 2009). The genetically modified endophyte *B. cepacia* G4 increased toluene tolerance in the yellow lupine plant and reduced phytovolatilization of toluene by 70% (Taghavi et al. 2005).

10.5.5 Genetically Modified Microbial Strains and Rhizosphere Competence

Ecological fitness of PGPR strain is essential for evaluating the potential risks associated with the release of modified strain into the environment. With this view, De Leij et al. (1998) introduced modified *P. fluorescens* SBW25 into the pea and wheat rhizosphere and did not find any negative metabolic burden on indigenous rhizosphere bacteria. To observe strain performance and competitiveness on crop species, the same modified strain was co-inoculated on three different crops such as on barley, pea, and navy bean under controlled conditions. The wild-type strain Q8r1-96 outcompeted Z30-97 on barley, but both strains maintained similar population densities on navy bean. Surprisingly, the engineered strain displaced the wild type on pea (Ryan et al. 2009 and references therein), suggesting that the crop species modulates strain competitiveness and must be considered when assessing the potential fate and the risk posed by the release of recombinant strains into the environment.

10.5.6 Future Research Orientations for Genetic Modification

The plant rhizosphere can be modified using different approaches, such as selection of crop species and varieties, introduction of microorganisms or soil amendments, and by genetic modification of plant and microbial activities. The emergence of molecular techniques now allows the direct manipulation of genes that influence rhizosphere functions present either in the plant or in the rhizospheric microbes. Genomics has given rise to metagenomics, which allows mass sequencing to aid the rapid exploration of microbial diversity of the rhizosphere. Though there are a number of encouraging avenues in rhizosphere modification, it remains a challenge due to the lack of understanding of the complex chemical and biological interactions among plants and microbes in the rhizosphere. Fundamental issues like microbial abundance and diversity in the soil remain unresolved (Ryan et al. 2009 and references therein).

Social acceptance regarding genetically modified organisms is also a major issue. These issues are relatively small in Canada, China, Japan, and the USA but are very great in Europe, even among members of the scientific community. However, the demands of an ever-increasing population are closely related to a risk of reduction of arable surface area (for instance, in fertile river deltas, urban areas, or lowlands). Also, environmental pollution through industrial waste and use of agrochemicals are major concerns for sustainable agriculture. To address these issues, safe alternatives such as nonpolluting solutions, novel natural biocontrol agents, and possibly genetically modified options are important. The scientific community should put more and continuous emphasis in this positive direction. Thus, the public of the future may benefit from safe, sustainable, and environmentally sound agricultural practices.

10.6 Bacteria Improve Plant Growth and Crop Yield

Microorganisms use a range of mechanisms, including N_2 fixation by the nitrogenase enzyme, nitrate reductase activity, siderophore production, phytohormone synthesis, etc., for enhancing plant growth and development both under normal and in stress environments (Fig. 10.2). To preserve ecological diversity and use sustainable agriculture to restore crop productivity, a new concept was raised using "environmentally friendly" N_2-fixing bacteria as a mode of increasing crop yield (Okon and Labandera-Gonzálezb 1994). Both nitrogen-fixing bacteria and free-living rhizospheric bacteria (e.g., *Pseudomonas*, *Bacillus*, *Azotobacter*, *Azospirillum*) are involved in growth promotion and yield increment of legumes, cereals, and other crops.

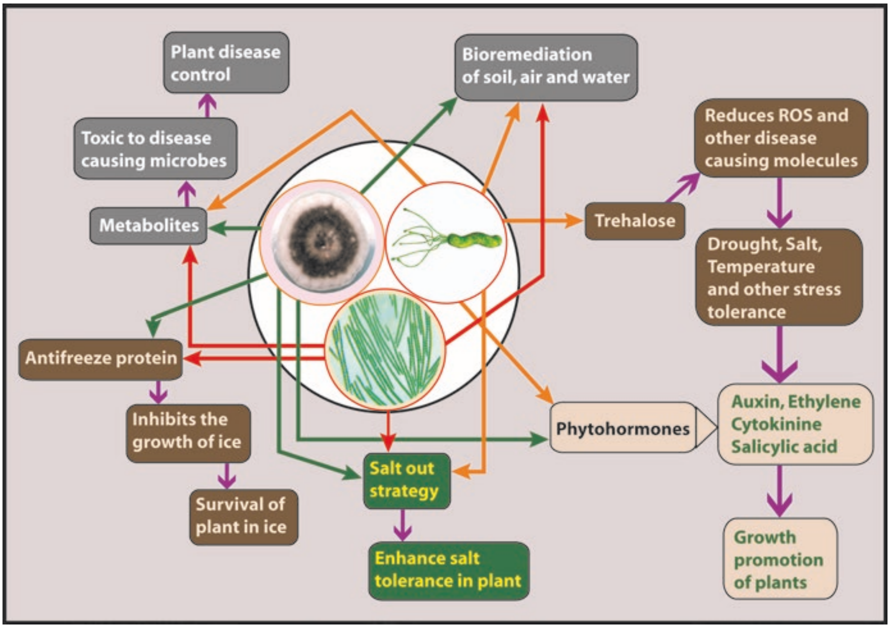

Fig. 10.2 Roles of soil microbes on plant growth and enhancement of stress tolerance

10.6.1 Phytohormones Produced by Microbes

Microbes are significant sources of major plant hormones: auxin, cytokinin, gibberellin, abscisic acid, and ethylene; nowadays, many microbial sources of phytohormones have been identified. Phytohormones of microbial origin can alter plant physiology and are able to cause diverse outcomes ranging from pathogenesis to promotion of plant growth (Spaepen 2015). Microbes that produced different phytohormones which played critical roles in growth and developments of plants are mentioned in Table 10.2. Data on auxin production is most widely available. These phytohormones have potential for agricultural uses, and the microbial production of plant hormones may have a bright future in sustainable agriculture.

10.6.2 IAA Produced by Bacteria Enhances Plant Growth Even Under Saline Conditions

Indole-3-acetic acid (IAA) or auxin is a plant hormone that has roles in growth, development, and behavioral processes in the plant life cycle. Auxin is involved in all developmental stages, from the cellular level to whole-plant development, and is regulated in different pathways in the plant body. In the plant cell, auxin biosynthesis occurs in a two-step biochemical reaction from the amino acid tryptophan via the products of the gene families TAA1/TAR and YUCCA (Cheng et al. 2006; Stepanova et al. 2008). Auxin may also be converted reversibly to other forms by many other enzymes. However, after biosynthesis auxin is moved from cell to cell via different carrier proteins, among which the PIN family and the ABCB family are the most studied (Zazimalova et al. 2010). These carriers facilitate compartmentalization of auxin in plant cells/tissues in a coordinated way and thereby take part in the development of the plant. Although excess amounts of auxin have negative effects on plants, judicious application ensures optimal growth. The IAA is not only produced in plants but also by microbes, especially by bacteria. Soil is one of the major sources from which many IAA-producing bacteria have been identified, and mining is still continuing. These beneficial bacteria are very much essential for sustainable agriculture. The effect of the rhizospheric bacteria *Azotobacter chroococcum*, two strains of *P. fluorescens*, and *B. subtilis* on the growth and yield of onion was assessed by Colo et al. (2014). The result showed that *B. subtilis* was the best producer of IAA, whereas *P. fluorescens* strains were better at producing siderophores and solubilizing phosphates. The *B. subtilis* and *Azotobacter chroococcum* variants produced the highest onion yield. The IAA-producing bacterial strains with growth-promoting traits were isolated by Khiangte and Lalfakzuala (2017).

Salt is a major limiting factor for seed germination and seedling growth due to its toxic effects. This effect can be alleviated by employing phytohormone-producing

Table 10.2 Phytohormone-producing microbes and their functions

Name of strains	Functions	References
Auxin-producing microbes		
B. megaterium ST2-1	Enhanced root and shoot growth and chlorophyll content of plants under controlled conditions through the production of auxin	Mohite (2013)
P. putida GR12-2	Enhanced root growth of canola through the production of auxin	Patten and Glick (2002)
Aspergillus niger BHUAS01; *Penicillium citrinum* BHUPC01	Increased chickpea (*Cicer arietinum*) growth by producing auxin	Yadav et al. (2011)
B. cereus A-139	Increased growth of lateral root in *Arabidopsis* and mungbean by producing auxin	So et al. (2009)
Enterobacter cloacae MSR1	The length of the primary roots, the number of secondary roots, and root dry weight of *Pisum sativum* and the root growth of alfalfa were significantly increased by inoculation with bacteria producing auxin	Ashraf et al. (2016)
B. amyloliquefaciens FZB42	Inoculated plants showed higher root dry weight and increased accumulation of N, P, and K	Mohite (2013)
P. stutzeri P3	Capable of producing IAA in vitro and enhance plant growth	Lata et al. (2006)
P. fluorescens AK1 and AK2	Bacterial inoculation increased root growth in rice due to the production of auxin	Karnwal (2009)
B. subtilis PRBS-1 and AP-3	IAA-producing bacterium, stimulated outgrowth of roots in soybean	Araújo et al. (2005)
Erwinia herbicola 299R	Produced significant amount of indole-3-acetic acid (IAA) in artificial media	Brandl and Lindow (1998)
Cytokinin-producing bacteria		
B subtilis IB-22	Stimulates amino acid deposition in wheat roots due to the production of cytokinin	Kudoyarova et al. (2014)
P. fluorescens G20-18	Acts as a biocontrol agent against *P. syringae* in *Arabidopsis* due to the production of cytokinin	Großkinsky et al. (2016)
B. licheniformis Am2; *B. subtilis* BC1; *P. aeruginosa* E2	Cytokinin-producing strain capable of accelerating cell division in cucumber	Hussain and Hasnain (2009)
Rhizobium fredii USDA 205; *Bradyrhizobium japonicum*	Has potential for stimulating cortical cell division in legume roots due to the production of cytokinin	Dawn and Barbara (1989)

Salicylic acid-producing strains		
B. licheniformis MML2501	Inhibited mycelial growth of fungal pathogens. Can be used in crop protection through systemic resistance induced by the production of salicylic acid	Shanmugam and Narayanasamy (2009)
P. fluorescens WCS374r	Induced systemic resistance in rice against the leaf blast pathogen *Magnaporthe oryzae* and also in radish due to the production of salicylic acid	Ran et al. (2005); de Vleesschauwer et al. (2008)
P. fluorescens CHA0; *P. aeruginosa* 7NSK2	Produced salicylic acid in association with grapevine that confers a systemic resistance against *Botrytis cinerea*	Verhagen et al. (2011)
Azospirillum brasilense Cd; *Azospirillum lipoferum* USA 5b	Improved growth of leaf and root of rice due to secretion of gibberellins	Fabricio et al. (2001)
Photorhabdus temperata M1021	Increased plant length, chlorophyll content, and fresh and dry biomass of rice through secretion of gibberellins	Ullah et al. (2014)

bacteria. The bacterial strain *P. aurantiaca* TSAU22 produces the phytohormone IAA and can alleviate salt stress (Egamberdieva 2009). This strain increased seed germination (from 54% to 90%) and seedling growth of cotton. Dormancy of wheat induced by salinity can be broken by the IAA-producing bacteria *P. aurantiaca* TSAU22, *P. extremorientalis* TSAU6, and *P. extremorientalis* TSAU20 (Egamberdieva 2009; Dhakal et al. 2016). Root growth of wheat seedlings was increased up to 25% under nonsaline conditions, while under saline conditions root growth was increased up to 52%. Amelioration of salt effects on seedling growth of soybean was also reported (Jabborova et al. 2013). The IAA-producing bacterial strain *P. putida* TSAU1 significantly increased soybean seedling root growth up to 29% under nonsaline condition and up to 86% at 100 mM NaCl. The IAA-producing *Kocuriatur fanensis* strain 2M4 was tested on groundnut (*Arachis hypogaea* L.) under nonsaline condition and found that total plant length and fresh biomass were increased by 18 and 30%, respectively. In saline soil the tested isolate restored the increased total plant length and fresh biomass of groundnut seedlings up to 17 and 13%, respectively (Goswami et al. 2014). Growth promotion activity of IAA-producing bacterial isolates was also reported in tomato and barley (Gajendramurthy et al. 2017).

10.6.3 The Involvement of Bacterial Gibberellins (GA_3) in Plant Growth and Yield Promotion

Gibberellins (GAs) are a large group of natural biomolecules, tetracyclic diterpenoid acids which are involved in physiological and developmental processes of plants. These processes include seed germination, seedling emergence, the growth of the stem and leaf, floral induction, and the growth of the flower and fruit (Pharis and King 1985; Sponsel 2003; King and Evans 2003). However, gibberellins are produced not only by higher plants and fungi but also by bacteria (Gutiérrez-Mañero et al. 2001; MacMillan 2002; Datta et al. 2017a). Historically, the physicochemical characterization of bacterial gibberellin was first done by Atzorn et al. (1988) in *Sinorhizobium meliloti* and demonstrated the presence of four gibberellins: GA1, GA4, GA9, and GA20. There is no known direct role for gibberellin in fungi and bacteria; rather they can be considered as secondary metabolites that induce reactions in host plants that are beneficial to them. Chemical synthesis of GA and other hormones is complicated and the products are costly and of low purity, but GA obtained from microbes may overcome these shortcomings. The final products obtained through this method not only possess higher bioactivity and purity, but are also produced at much lower cost, which is highly desirable for sustainable agriculture. Several studies have been conducted to find and characterize GA-producing bacteria and examine their growth-promoting activities in plants.

Microbes dwelling in root nodules of legume plants sometimes modify the hormonal levels within the nodule by producing GA or gibberellin-like substances, thereby affecting plant cell metabolism (Cassán 2003). Dobert et al. (1992) observed a significant internode elongation in lima bean when inoculated with a specific *Bradyrhizobium* sp. (strain 127E14) that was not seen in plants inoculated with other compatible *Bradyrhizobium* species. Joo et al. (2009) identified *Burkholderia* sp. KCTC 11096BP as a gibberellin-producing bacterium. The gibberellin-producing bacterium *B. cereus* MJ-1 caused a 1.38-fold increase in fresh weight (fw) and a 1.28-fold fresh weight gaining roots of pepper plant (Joo et al. 2006).

GA-producing bacteria also increase the growth and nutritional quality of leafy vegetables. Radhakrishnan and In-Jung (2016) demonstrated a significant increase in shoot length, shoot fresh weight, and leaf width of lettuce when the plants are associated with the bacterial strain *B. methylotrophicus* strain EK2. Gibberellin produced by this bacterium is responsible for enhanced growth of lettuce. Endophytic GA-producing bacteria also increase plant growth. The endophytic bacterium *B. amyloliquefaciens* RWL-1 produced GA in rice plants and regulated a few other endogenous phytohormones (Shahzad et al. 2016). The endophytic bacterium *B. subtilis* LKM-BK promotes seedling growth of cocoa (Ishak et al. 2016) and *Sphingomonas* sp. LK11 promotes growth of tomato plants (Khan et al. 2014; Kumar et al. 2015; Meena et al. 2018b).

Microbes can play a significant role in plant growth and development. It is unlikely that plant growth acceleration by rhizobacteria is a result of the combined action of several mechanisms; phytohormone production by microbes has a direct positive influence on the growth and yield of important crop plants (Arkhipova et al. 2005; Idris et al. 2007; Sihag et al. 2015). Therefore, use of these plant growth-promoting bacteria can reduce the indiscriminate use of fertilizer in the field. Their judicious application will enhance sustainable agriculture.

10.6.4 Trehalose Biosynthesis in Plants from Microbial Origin Confers Stress Tolerance

Trehalose is a nonreducing disaccharide composed of two glucose units; it is an α-D-glucopyranosyl-(1→1)-α-D-glucopyranoside. It is also known as mycose and has been identified in many organisms: bacteria, yeast, fungi, higher and lower plants, insects, and other invertebrates. It is an energy source, protein or membrane protectant, and osmolyte (Elbein et al. 2003). Initially it was considered a rare sugar, but later was discovered in many organisms. Trehalose is multifunctional, and some functions are specific to certain species (Iordachescu and Imai 2008). It appears to act as an energy source for microbes and also protects them from dehydration (Crowe et al. 1992; Drennan et al. 1993; Elbein et al. 2003). Trehalose produced by microbes can protect the plant from different stress conditions to varying degrees. Trehalose produced by the desiccation-sensitive bacterial strain *P. putida* KT2440 can protect pepper and tomato plants from drought (Vilchez et al. 2016; Sofi et al. 2018). Research found that the products of the *otsAB* genes are responsible for trehalose production in the bacterial strain *P. putida* KT2440. Increased level of trehalose is known as an osmoprotectant under several different abiotic stresses, including high salt, drought, and unfavorable temperature. Trehalose-producing microbes are resistant to both acid and high temperature. Trehalose can form a vitreous phase during dehydration to protect biomolecules from damage by drought and salt (Glick 2012). A few approaches have been developed to increase the concentration of trehalose in plants. Firstly, some growth-promoting bacteria in association with plants are capable of producing ACC deaminase and trehalose naturally, which can protect plants from stresses. Cyanobacteria can also produce and accumulate trehalose under stress conditions. During salt stress, cyanobacterial strain can produce trehalose and other compatible solutes that confer different degrees of salt resistance (Sakamoto et al. 2009; Klahn and Hagemann 2011). Application of such approach in the agricultural field is helpful for increasing productivity and an effective tool for sustainable agriculture.

10.7 Cyanobacterial Salt Stress Tolerance Modulation

Cyanobacteria are photosynthetic, unicellular, aquatic, free-living, and often colonial organisms. Their cell can be large enough to see with the naked eye (cell size range 0.5–40 μm) and they have been present on this planet for 3.5 billion years. They are frequently known as "blue-green algae" as they are aquatic and photosynthetic. Cyanobacteria are relatives of other bacteria (prokaryotes), but some of them later became incorporated into eukaryotic entities through evolutionary processes when they took up residence inside the plant cell as chloroplast through endosymbiosis. Cyanobacteria are agriculturally important as they are capable of surviving and thriving under extreme conditions such as desiccation, high temperature, extreme pH, and high salinity.

Some cyanobacteria are nitrogen fixers and play an important role in plant growth and development. Cyanobacteria that are capable to fixing the atmospheric nitrogen can be used as valuable biological input for improving soil texture, conserving soil moisture, scavenging the toxic sodium cation from the soil, and also for improving the soil properties. There is a symbiotic relationship between rice plants, the fern *Azolla*, and the cyanobacterium *Anabaena*. There is a direct symbiotic relationship between *Anabaena* and the fern, where *Anabaena* colonizes the fern leaves and the latter one fixes atmospheric nitrogen. The fern thus provides an inexpensive natural fertilizer to the rice when it dies at the end of the season (Vaishampayan et al. 2001; Verma et al. 2015). Culture filtrates of the cyanobacterial strains *Calothrix ghosei*, *Hapalosiphon intricatus*, and *Nostoc* sp. isolated from wheat rhizosphere enhanced germination, length of radicle, and coleoptile of wheat (Karthikeyan et al. 2009). Besides rice, their influence on other crop plants, e.g., wheat, tomato, pulse, and vegetable, is also documented (Kaushik and Venkataraman 1979; Karthikeyan et al. 2007). Cyanobacterial strains also improve soil health. Chamizo et al. (2018) conducted an experiment using non-nitrogen-fixing (*Phormidium ambiguum*) and nitrogen-fixing (*Scytonema javanicum*) cyanobacterial species on different textured soils to examine cyanobacterial biocrust development and thereby change in the physicochemical properties of soil. Electron microscopy analysis found a contrasting structure of the biocrust induced by these two cyanobacteria. The strain *S. javanicum* increased the total organic C and total N content, while *P. ambiguum* increased the total exopolysaccharide (EPS) content and soil penetration resistance. On the whole, the improvement in soil fertility and stability supports the viability of using cyanobacteria to restore degraded arid soils. Cyanobacterial inoculum could also supplement up to 20% nitrogen for rice cultivation in saline soil (Aziz and Hashem 2003; Meena et al. 2017c).

Salt is a major limiting factor for plant growth and crop production. To mitigate the salt problem while keeping natural resources undisturbed, microbial inoculation is an eco-friendly alternative to synthetic and hazardous chemical. Cyanobacteria can improve the growth and yield of crops and can be used as an effective tool for management/restoration of soil fertility. Certain cyanobacterial strain also improves the physicochemical properties of the saline soil by enriching them with carbon, nitrogen, and available phosphorus. Traditionally, chemically synthesized agents like gypsum, sulfur, or excessive irrigation are applied to reduce salinity, but they are not cost-effective or environmentally friendly. Salt-affected soils are less productive and impermeable to water. Due to poor hydraulic conductivity and aeration, saline soil becomes poor and less fertile (Singh et al. 2016; Verma et al. 2015a). Cyanobacteria can be used to treat alkaline soils, and soil fertility can be improved by subsequent cultivation of cereals, sugarcane, and horticultural crops. Cyanobacteria use the “salt-out strategy” to address the changing salt concentrations. At high salt concentration, cyanobacteria synthesize and accumulate osmoprotective compounds, maintain low internal concentration of inorganic ions, and express a set of salt stress protein. Moreover, under different abiotic stress conditions, cyanobacterial cells showed rapid expression of several stress-regulated proteins and modified protein synthesis program. To maintain low intracellular salt concentration, inorganic solutes like disaccharides (sucrose, trehalose, and glucosylglycerol), quaternary amines (glycine betaine), and free amino acids (glutamine) are produced in the cell which in turn minimize the osmotic stress on the cell. These compatible solutes help cyanobacteria to survive in saline desert soils (Oren 2000). The most important ecophysiological features of cyanobacteria are their ability to slow their growth rate over a wide temperature range and their tolerance to desiccation, freezing, and salinity stress, which makes them dominant in these environments. They have the ability to tolerate very low water potential and extracellular mucopolysaccharides slow down the flow of liquid water during freezing.

Saline soils typically have high pH values, large amount of carbonate, and high exchangeable sodium. Cyanobacteria produce biofilm and conserve organic C, N, and P and soil moisture, and convert the sodium clays into calcium clays (Singh et al. 2016; Meena et al. 2015b). They add organic matter and N to saline soils, which help to bind the soil particles together, thus improving soil permeability and aeration (Maqubela et al. 2009). Excretion of polysaccharide and lipid by cyanobacteria improves the physicochemical quality of saline and alkaline soils. Cyanobacterial species such as *Anabaena oscillarioides*, *A. aphanizomenoides*, and *Microcystis aeruginosa* exhibited salt tolerance ranging from 7 to 15 g l^{-1} (Coutinho and Seeliger 1984; Moisander et al. 2002). There is a positive correlation between NaCl tolerance and exopolysaccharide (EPS) production in some cyanobacteria (Ozturk and Aslim 2010). The EPS produced by cyanobacteria are believed to protect bacterial cell from desiccation, heavy metals, or other environmental stresses, including salt stress. Elevated level of exopolysaccharide increases protection. The cyanobacterial strain *Synechocystis* sp. BASO444 produces large amounts of EPS (500 mg l^{-1}) and showed high tolerance against salinity (Ozturk and Aslim 2010).

10.8 Conclusion

Although the size of an individual soil microorganism is very small, it has a very significant effect on the physical, chemical, and biological process in the soil that is directly and indirectly critical for the growth and development of plants and animals. Soil microbes play important roles in the cycling of many nutrients that are essential for life. Different nutrients like carbon, nitrogen, phosphorus, potassium, zinc, calcium, manganese, and silicon are continuously recycled by microbes. Nutrient recycling is not only essential for plants but also for other forms of life because it provides the materials to produce amino acids, proteins, DNA, and RNA, those that are essential for all living system.

Industrialization and modern agricultural practices are putting increasing negative pressures on agricultural soil and water by releasing large quantities of hazardous waste, heavy metals, and organic contaminants that are a serious problem not only for agriculture but also for human health. Trace amount of different heavy metals like lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), zinc (Zn), uranium (Ur), selenium (Se), silver (Ag), gold (Au), nickel (Ni), and arsenic (As) is useful for plants, but upon excess uptake they reduce plant growth by imposing negative effects on plant photosynthesis, plant mineral nutrition, and the activities of essential enzymes. Bioremediation is an avenue for the removal of heavy metal ions from polluted environment using the activities of algae, bacteria, fungi, or plants. Bioremediation using microorganisms is sustainable because they help to recover the natural state of the polluted environment with long-term environmental benefit and cost-effectiveness. Detoxification of heavy metals by microorganisms can occur naturally or through the addition of microbial strains from nature or developed by genetic modification. Microorganisms use biosorption, adsorption, compartmentalization of heavy metals into intracellular molecules, metal binding, vacuolar compartmentalization, extracellular mobilization, or immobilization of metal ions to reduce active concentration of metal ions present in polluted environments.

Genes responsible for growth promotion have been proven effective tool for strain improvement through modifying their expression timing and level or by transferring and expressing them in alternative hosts for enhancing plant growth and improving the fitness of the modified strain. Microorganisms modified by genetic engineering have enhanced specific characteristics, such as the ability to degrade a wide range of contaminants for the bioremediation of soil, water, and activated sludge, enhancing the biotic and abiotic stress tolerance of plants, enhanced phytohormone production, etc. Modified strain can survive and remain active in harsh environment. Plant-associated degradation of pollutants in soil by genetic modification of endophytic and rhizospheric bacteria is an important means for the remediation of contaminated soil. Microorganisms use a range of mechanisms, including N_2 fixation by the nitrogenase enzyme, nitrate reductase activity, siderophore production, and phytohormone synthesis for enhancing plant development and growth both under normal and stress environments. Auxin, cytokinin, gibberellin, abscisic acid, and ethylene are major plant hormones, and more phytohormones have also been identified. Diverse microbial species have the ability to produce phytohormones, and these are now being widely used in agriculture for enhancing plant growth and stress tolerance.

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Enzymes in Relation to Soil Biological Properties and Sustainability

11

Naveen Datt and Dhanbir Singh

Contents

Abstract

Deterioration of soil health is of concern for human, animal and plant health, because air, groundwater and surface water consumed by humans are adversely affected by contaminated soil. Soil microorganisms play an important role in the transformation of carbon (C), nitrogen (N), phosphorus (P), sulphur (S) and iron (Fe). Soil biological properties, e.g. microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), microbial biomass phosphorus (MBP), and activities of soil enzymes, viz. amylase (AMY), dehydrogenase (DHA), cellulase (CA), pectinase (PA), phenoloxidase (POA), urease (UA) and phosphatase (PHA),

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respond quickly to change in soil quality and have been considered better indicator than soil physical and chemical properties. Soil enzymes play a major role in the energy transfer through decomposition of soil organic matter (SOM) and nutrient cycling and thus have a substantial role in maintaining soil health. Enzymes are the vital activators in life processes of soil microorganisms and the products of which stabilize soil structure. Although microorganisms are the major source of soil enzymes, plants and animals also contribute in a significant manner to the enzyme pool. Their activities are closely related to the biological properties of soil. Hence, soil enzymes are indicators for soil microbial community structure and for the effect of soil treatments or climatic factors on soil health and soil fertility. The possible role of soil enzymes in organic matter (OM) decomposition and soil health maintenance can help in the management of soil fertility in agricultural ecosystems.

Keywords
Biological properties · Soil enzymes · Soil health · Sustainability

Abbreviations

AMY	Amylase
ASA	Arylsulphatase
C	Carbon
CA	Cellulase
CATA	Catalase
DHA	Dehydrogenase
Fe	Iron
FYM	Farmyard manure
GALA	Galactosidase
GLUCA	Glucosaminidase
GSA	Glucosidase
H	Hydrogen
INV	Invertase
MBC	Microbial biomass carbon
MBN	Microbial biomass nitrogen
MBP	Microbial biomass phosphorus
N	Nitrogen
NAD	Nicotinamide dinucleotide
NADP	Nicotinamide dinucleotide phosphate
NPK	Nitrogen, phosphorus and potassium
O	Oxygen
OM	Organic matter
P	Phosphorus
PA	Pectinase

PERA	Peroxidase
PHA	Phosphatase
POA	Phenol oxidase
PROA	Protease
PSMs	Plant-soil microorganisms
S	Sulphur
SOC	Soil organic carbon
SOM	Soil organic matter
SRR	Specific respiration rate
UA	Urease

11.1 Introduction

Global demand and consumption of agricultural crops for food, feed and fuel is increasing at a rapid rate. This is a challenging task to meet the food requirements of present 7.65 billion people in the world. This, in turn, is exerting pressure on our valuable resource soil. Besides this global warming, decreasing soil fertility and sustainability of agricultural production, declining organic matter (OM) in the soil, soil and water pollution and others are the emerging issues in the crop production and quality produce which are directly or indirectly controlled by the microbial activity. Carbon sequestration is the main component for improving microbial activity, reviving soil fertility and sustainability in the soil. Improving carbon sequestration by all means including recycling of crop residues, green manuring, composting and reduced tillage is the key component for reviving soil fertility and sustainability. Solar energy initiated photosynthetic life in the primordial earth, and as a consequence of which, earth's primitive atmosphere changed into an oxygenated condition. Since then, evolution of life has progressed on divergent lines and the elements carbon (C), nitrogen (N), hydrogen (H) and oxygen (O) have undergone a series of recycling processes through assimilation and decomposition, thereby creating a biosphere wherein microorganisms, plants, animals and man have lived in equilibrium for centuries. In recent years, attempts have been made to estimate the amount of C and N transferred within the different ecosystems of the biosphere, but the figures for two elements in the biosphere may, however, be taken as broad guidelines. According to an estimate, 700 billion tonnes of carbon in the atmosphere and almost an equal amount is locked in the dead organic matter on land; 450 billion tonnes of carbon in living plants interchange with the atmospheric carbon through natural processes. Nonetheless, the pathways by which the elements get transferred within different ecosystems have been clearly understood, and some of them fall in the preview of plant-soil microorganism (PSM) interactions. Apart from the C and N transformations in the biosphere which are of great magnitude, other elements like O, H, phosphorus (P), sulphur (S) and iron (Fe) undergo mutual transfers in the biosphere between ecosystem, and some of these changes are linked with plants and soil microorganisms. Since living entities' metabolism is completed by enzymes, likewise the role of enzymes in maintaining soil health and its environment cannot be ignored. Enzymes are proteins that catalyse chemical reactions to proceed at faster rates without undergoing permanent alterations. They lower the activation energy of the reaction thus causing the reaction to proceed at faster rates. Soil enzymes are similar to those in other biological systems. However, the difference between enzyme activities in soils and those of other systems is that the source may be associated with living and nonliving components. Soil enzymes are the biological catalyst of innumerable chemical reactions necessary for life processes of microorganisms in soils, decomposition of organic residues, cycling of nutrients and formation of organic matter and soil structure (Dick 1994; Meena et al. 2018a). The enzymatic activity in the soil is mainly of microbial origin, being derived from the intracellular, cell-associated or free enzymes. A unique balance of chemical, physical and biological (including microbial especially enzyme activities) components contribute to maintaining soil health. Ellert et al. (1997) in their findings concluded that to combat the disturbances, such as drought, climate change, pest infestation, pollution and human exploitation including agriculture, healthy soils are essential for the maintenance of the integrity of terrestrial ecosystems. Deterioration of soil health is of concern for human, animal, and plant health because air, groundwater, and surface water consumed by humans can be adversely affected by mismanaged and contaminated soil (Singer and Ewing 2000; Yadav et al. 2017a; Sofi et al. 2018). As soil is part of the terrestrial environment and supports all terrestrial life forms, protection of soil is therefore of high priority although understanding of soil enzymes activities is a crucial factor in assuring that soil enzymes remain healthy. A better understanding of the role of all enzymes' activity in maintaining the soil health will potentially provide a unique opportunity for an integrated biological assessment of soils due to their crucial role in several soil biological activities, their ease of measurement and their immediate response to changes in the soil environment. Although there have been extensive studies on soil enzymes, little has been reported on their role in maintaining soil health. Thus, it is essential to understand the role of these enzymes' activity and their efficiency to maintain soil health for the future betterment of soil research and soil biology and sustainability in productivity. Several attempts have been made to show soil enzyme activity-fertility-crop productivity relationships, but strong correlations can be expected only in unmanaged ecosystems or low-input agricultural systems because, in managed systems, other factors may confound or override the relationship between soil biological activity and plant productivity. Alternative systems involving legume green manures had improved soil structure and enzyme activity as compared to conventional systems. Increased activities of several enzymes have been shown with organic amendments, green manure/crop residues (Rao and Pathak 1996; Meena and Meena 2017) and municipal refuse. Cultivation depresses enzymatic activity (Gupta and Germida 1988). Majority of studies have reported a significant correlation between soil enzymes and plant yield, whereas some studies show no close relationship. For example, mean grain yield of different crops under rain-fed production systems was positively correlated with dehydrogenase (DHA), arylsulphatase (ASA) and urease activities (UA) in soil (Mandal et al. 2007; Meena et al. 2016; Yadav et al. 2018a).

The plant productivity is under the influence of many factors like soil quality, plant genotype, biotic and abiotic stresses, etc. Further, in managed ecosystems, many other factors may influence the relationship between enzyme activity and plant productivity. In this chapter, biological indicators of soil quality, major soil enzymes and their functions in nutrient cycling, soil health and yield sustainability, are discussed. The effects of crop rotation, intercropping, tillage, green manuring, fertilizers and pest management on soil enzymes are also discussed. Besides, the influence of climatic factors like elevated carbon dioxide (CO_2), temperature or drought on soil enzymatic activities have also been addressed.

11.2 Role of Microflora in Soil Processes

The changes occur quickly in soil biological properties and have been considered as better indicators than soil physical and chemical properties in evaluating soil quality (Nannipieri et al. 1990). Soil biological components occupy only less than 0.5% volume of soil and usually constitute up to 10% of soil organic matter (SOM). Plant roots contribute 5–15% of the living component of SOM, and 85–95% is contributed by soil organisms. Among different soil organisms, 5–10% is macro- and mesofauna and remaining 90–95% microorganisms. Soil microorganisms, mainly bacteria and fungi, thus are the major components of soil microbial community contributing to 80–90% of soil biological activity (Pankhurst 1999; Kakraliya et al. 2018; Meena et al. 2015c). Soil microorganisms play a critical role in soil biological activities and in maintaining soil health, ecosystem functions and crop production. The activities of certain microorganisms such as fungi, algae and bacteria affect the soil structure by encouraging soil aggregation due to polysaccharide formation during the decomposition process. These directly affect the different soil physical properties, the studies of which determine vulnerability to soil erosion. Soil microorganisms are central to decomposition processes and nutrient cycling. Some soil organisms can be detrimental to plant growth by causing plant diseases; however, many of them can protect crops from pest and disease outbreaks through biological control and reduced susceptibility. The activities of certain organisms determine the C cycle—the rate of C sequestration and gaseous emission and SOM transformation. Symbiotic relationships, especially of rhizobia with legumes bacteria and mycorrhiza with crop plants play a key role in the uptake of nutrients and water and contribute to the maintenance of porosity and organic matter content, through their growth and biomass. A group of soil microorganisms referred to as plant growth-promoting rhizobacteria secrete plant growth hormones such as indole acetic acid, gibberellins and cytokinins which enhance seed germination, root development and plant growth. Soil microbiological and biochemical properties such as microbial biomass, soil respiration and microbial community structure and soil enzyme activities, etc. have been identified as important soil quality indicators (Chandra 2013). A number of microbiological and biochemical parameters have been suggested as indicators of soil quality (Table 11.1).

Table 11.1 Biological indicators of soil quality

Soil quality indexes	Relationship to soil condition or function
Microbial biomass carbon (MBC)	Indicator of cropping, land use and management history, organic matter change
Microbial biomass nitrogen (MBN)	Land use and management, effects on soil fertility, N availability
Microbial biomass phosphorus (MBP)	Land use and management, effects on soil fertility change, P availability
Microbial quotient (MBC/OC)	Indicator of cropping, land use, and management history, organic matter change, soil pollution
Specific respiration rate (SRR)	Indicator of environment stress, measured together with MBC and OC
Microbial metabolic quotient (SRR/MBC)	Indicator of cropping, land use and management history, organic matter change and soil pollution
Ratio of SRR to OC	Indicator of soil pollution
Microbial community structure	Indicator of heavy metal contamination, soil erosion fertility restoration, management, ecosystem function, etc.
Soil enzymes (PHA, ASA, and DHA, etc.)	Indicator of cropping and management history and OM change, soil degradation and contamination, climate change
Free-living diazotrophic bacteria	Indicator of soil pollution
Fungal/bacterial ratio	Land use soil management
Ratio of direct counts/culturable counts	Indicator of heavy metal contamination and soil degradation

Modified from Chandra (2013)

11.3 Major Soil Enzymes and Their Functions

The enzymes present in soil are of two types: (i) constitutive, always present in nearly constant amount in a cell and not affected by addition of any particular substrate, e.g. pyrophosphatase, and (ii) inducible, present in trace amount or not at all, but quickly increase in concentration when a substrate is present, e.g. amidase. The soil enzymes and their functions are depicted in Fig. 11.1. Major groups of enzymes are briefly described as follows:

(i) Oxidoreductases are glucose oxidase, catechol oxidase and catalase with the substrate glucose, catechol and hydrogen peroxide. Enzymes in this group are responsible for polymerization of phenolic compounds. The most commonly studied oxidoreductases in soils are dehydrogenases.
(ii) Transferases are involved in the group transfer from one molecule to another. An important enzyme in this group is thiosulphatase S transferase that performs the intermediate step in oxidation of elemental S which is found in small amounts in soils.
(iii) Lyases are involved in the cleavage of bonds other than hydrolysis or oxidation. Glycosidases are group of enzymes that act on glycosyl compounds including glucoside hydrolases: α-glucosidase (GSA), β-GSA, α-galactosidase (GALA), β-GALA and N-acetyl β-D-glucosaminidase.

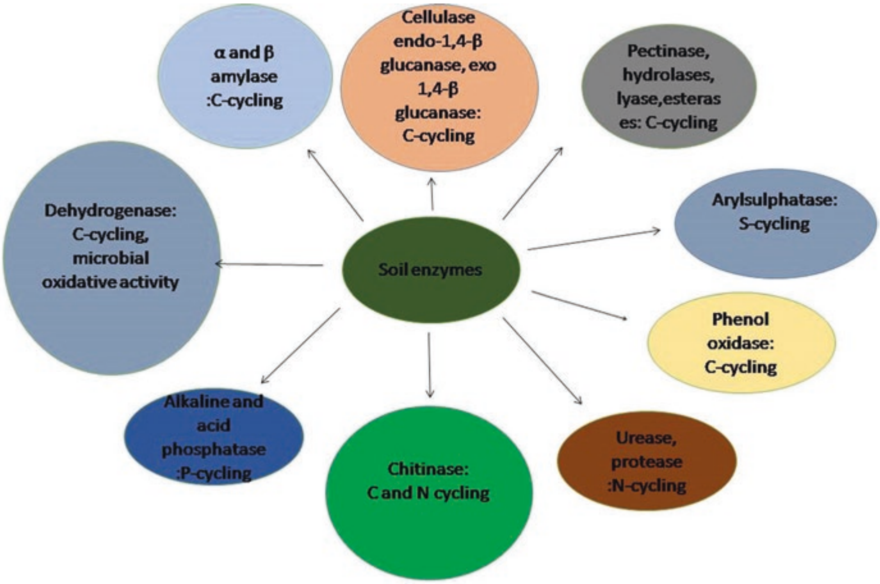

Fig. 11.1 Soil enzymes and their functions

(iv) Aryl amidase (α-aminoacyl-peptide hydrolase) is the enzyme that catalyses the hydrolysis of an N-terminal amino acid from peptides, amides or arylamides. It is believed that enzyme catalyses one of the initial reactions in N mineralization because it is involved in the release of amino acids from the SOM. These amino acids released by the activity of arylamidase are the substrates for amidohydrolase involved in N-mineralization.

(v) Amidohydrolases: L-asparaginase, L-aspartase, L-glutaminase, amidase and urease are a group of enzymes involved in hydrolysis of organic-N in soils. Urease is the enzyme that catalyses the hydrolysis of urea into CO_2 and NH_3. L-Aspartase catalyses the hydrolysis of L-aspartate to fumarate and $NH_{3.}$

(vi) Phosphatases (PHA) are a large group of enzymes that catalyses the hydrolysis of esters and anhydrides of H_3PO_4 and plays a major role in mineralization of organic P.

(vii) ASA group includes arylsulphatase, alkyl sulphatase, steroid *sulphatase*, glucosulphatase, chondrosulphatase and myrosulphatase which hydrolyses sulphate esters. Hydrolases catalyse the reaction by cleavage of bonds and splitting of water molecules. This group of enzyme does not require a cofactor for activity, and they are more resistant for inactivation as compared to other groups of enzymes. The major soil enzymes used as soil function indicators and factors affecting soil enzymes are presented in Table 11.2. The assessment of reaction rates for important soil processes, soil productivity, microbial activity and effects of pollutants can be interpreted from activities of soil enzymes (Nare et al. 2014; Meena et al. 2015a; Kumar et al. 2018).

Table 11.2 Major soil enzymes and their functions

Enzyme	Source	Reaction catalysed	End product	Factors influencing enzyme activity
α-Amylase (α-AMY)	Plants, animals and microorganisms	Starch hydrolysis	Glucose and/or oligosaccharides	Management practices, type of vegetation, environment and soil types
β-Amylase (β-AMY)	Mainly plants	Starch hydrolysis	Maltose	
DHA	Microorganisms	Oxidation of organic compounds	Transfer of H to NAD or NADP (electron transport system)	Soil water content, temperature, pesticide, trace elements, management practice, pollution, etc.
Cellulase	Microorganisms, protozoa and termites	Cellulose endohydrolysis	Oligosaccharides	Temperature, pH, water, O_2 contents, quality and location of OM, mineral elements and fungicides
Endo-1,4-β glucanase				
Exo-1,4-β-glucanase		Cellulose cleavage at ends	Glucose and cellobiose	
β-GSA		Cellobiose hydrolysis	Glucose	
Pectinase hydrolases (endo- and exopolygalacturonase	Plants and microbes	Hydrolysis of pectic acid. Degrades pectic acid through an elimination reaction. Methyl ester bond of pectin	Mono galacturonic acid	Temperature and pH
Lyases (endopolygalacturonase lyase and exopolygalacturonase lyase)			Methanol, acetate, and H_2	
Esterase			Intermediary metabolites, CH_4, CO_2	
POA	Plants and microorganisms	Lignin hydrolysis	Humic substances	Soil pH, mean annual precipitation and temperature, SOM content, management practices, N enrichment, etc.
UA	Plants, microorganisms, and invertebrates	Urea hydrolysis	Ammonia and CO_2	Cropping history, organic matter, soil depth, management practices, heavy metals, temperature, and pH

(continued)

Alkaline phosphatase	Mainly bacteria	Hydrolysis of esters and anhydrides of phosphoric acid	Phosphate (PO_4)	OM, management practices, pollution, crop species, and varieties
Acid PHA	Plants, fungi, and bacteria			
Arylsulphatase (ASA)	Microorganism, plants, and animals	Hydrolysis of sulphate esters	Sulphate (SO_4^{-2})	Heavy metal pollution, pH, OM content composition and availability of sulphate esters
Protease	Microorganism and plants	N mineralization	Available N	Humic acid concentration, availability of C and N etc.
Chitinase	Microorganism and plants	Degradation and hydrolysis of chitin	Carbohydrate and inorganic N	Availability of N, soil depth, atmospheric CO_2 levels, etc.

11.4 Management Practices Influencing Soil Enzymes (Fig. 11.2)

11.4.1 Crop Rotation

Crop rotation is the systematic planting of different crops in a particular order over years in the same growing space. This process helps to maintain nutrients in the soil, soil enzyme activation, reduces soil erosion and prevents plant diseases and pests. Soil enzymatic activity is generally affected by crop rotations, reduced tillage and fallow. Martinez et al. 2007 studied the effect of alternative crop intensities (100 and 67%) of winter wheat, corn (*Zea mays*), proso millet (*Panicum miliaceum*), and fallow under no-tillage compared to the typical 50% crop intensity rotation under either conventional tillage and no-tillage in a 15-year experiment and concluded that combination of no-tillage and continuous cropping with reduced fallow frequency in two alternative (100 and 67%) cropping intensities have had a positive effect on soil quality parameters such as microbial populations and community composition only at 0–5 cm depth and several enzymes activities β-glucosaminidase (β-GLUCA), GSA and α-GALA and PHA and phosphodiesterase at 0–5 and 5–10 cm depths. In another study (Chu et al. 2016) on long-term fertilization, tillage and crop rotation effects on the activity of soil enzymes revealed that no-tillage increased POA, PERA, DHA and β-GLUCA in the top layer (0–10 cm) compared with conventional tillage, and effects of crop type and rotation were significant but different for each enzyme. POA was highest in continuous soybean (*Glycine max*) followed by continuous corn (*Zea mays*), corn-wheat (*Triticum aestivum*), clover (*Trifolium pratense*), continuous timothy (*Phleum pratense*) and continuous wheat. DHA was highest in timothy plots, followed by corn-wheat-clover and lowest in

Fig. 11.2 Management practices influencing soil enzymatic activities

continuous soybean. Cellulase (CA) was significantly higher in continuous timothy than in continuous soybean. Due to the sensitivity of soil enzymes to environmental factors, soil enzymes such as POA, DHA, cellulose and β-GLUCA are suitable indicators of soil quality. Enzymatic activity was more in cropping system with a cover crop. Further, they also concluded that fertilization increased CA and β-GLUCA but have mixed effects for POA, PERA and DHA. Crop rotation had a significant effect on DHA; microbial biomass after wheat harvest when preceding legume crops were grown in comparison to rice or maize (Chandra 2011; Meena et al. 2017a; Yadav et al. 2018b). In contrast, the burning of biomass has an adverse effect on the activity of soil enzymes. Saplalrinliana et al. (2016) concluded that the AMY, ASA, GSA, PRO and DHA were higher under longer fallow phase than that in short fallow phase and related with a higher quantity of accumulated forest litter as its accumulation was higher under longer fallow phase. However, the burning practice affected negatively the relationship of the length of the fallow phase and the activity of soil enzymes except for AMY.

Land use has variation in the microbial population, viz. bacterial, fungal and actinomycetes. Wide variation in the soil microbial population was recorded under different land use system in neutral to saline soil in the sub-mountainous zone of Punjab (Garcha et al. 2016; Mitran et al. 2018; Meena and Lal 2018). The total microbial population was maximum in the mixed forest followed by Sheesham (*Dalbergia sissoo*) plantation and kinnow orchards and least in the fodder crop (Napier hybrid bajra) and cultivated area of maize-wheat.

11.4.2 Intercropping

Intercropping is a practice of growing two crops simultaneously on the same field to economize the land and for obtaining higher returns. It is well known that plants exert species-specific effects on rhizosphere microflora and fauna because of the differences in amount and composition of root exudates (Baudoin et al. 2003; Meena et al. 2017b; Yadav et al. 2017b). The roots of various plant species are in direct contact under intercropping and rhizosphere communities of both plant species interact and resulting microbial group composition is likely to be a mixture of the species-specific communities but will be dominated by the community composition of one plant species. Song et al. (2007) reported from their findings on soil microbiological properties and diversity in rhizosphere of wheat, maize, and fava bean (*Vicia faba* ssp. Minor) grown in the field solely and intercropped wheat-faba bean, wheat-maize, and maize-faba bean in the second and third year after establishment of the cropping system that intercropping increased MBC and N, whereas it reduced MBN in the rhizosphere of wheat. In another study, Zhou et al. 2011 reported that soil POA and UA increased under intercropping of garlic with cucumber in the first two growing seasons. However, soil catalase activity (CATA) was higher under garlic-cucumber intercropping than under monoculture in the last two growing seasons. Soil UA was higher under onion-cucumber system followed by garlic-cucumber and significantly better than monoculture, and soil CATA was lower in intercropping than under monoculture. Soil bacterial community band numbers and diversity indices decreased with a growing season under monoculture. These indices were relatively stable under intercropping systems. Garlic-cucumber had a more positive effect on soil fungal community structure than the onion-cucumber system. In another study, Ahmed et al. (2013) concluded that intercropping pepper with green garlic improved soil microbial and biochemical properties and activities of invertase (INV), alkaline PHA and CATA, while UA was promisingly higher in pepper plots intercropped with normal garlic.

The legumes contribute significantly to soil fertility because of atmospheric N fixation and when grown in combination with grass, grass sp. add biomass C to the soil which increases the efficiency of legume component. The study conducted by Datt et al. (2012) revealed that introduction of legumes with the high-yielding grasses in the cropping system brought improvement in soil fertility and enzymatic PHA and DHA in dry temperate pastures of Northwestern Himalaya.

11.4.3 Conservation Tillage

Tillage breaks soil structure for easy emergence of seedlings, destroys weeds, incorporates plant residues into surface soil layers, destroys plant pathogens, etc. Tillage should be minimized for maintenance of soil organic matter. Soil microbial biomass carbon and counts of root nodule bacteria were higher by 18.8 and 11.0%, respectively, under zero tillage than under deep tillage up to 20 cm depth in a 4-year study at ICRISAT, India (Lee et al. 1999). In another study, Roldan et al. (2005) concluded higher β-GSA, PHA, DHA, UA and PROA activities in conservation tillage than conventional tillage. Enzyme activity and hence microbial activity were correlated positively with the microbial biomass which in turn was related with the maintenance of soil organic matter. Bonanomi et al. (2011) reported a positive correlation between enzymatic activity and total soil organic carbon (SOC). Forest cleaning, cropping and management practices affect the soil microbial activity, a fact attributed to fewer C inputs. Similarly, the intensively managed soils show a decrease in microbial activity in comparison to well-managed pastures (Cardoso et al. 2013; Meena et al. 2018b; Gogoi et al. 2018). The long-term (19 years) study on effects of two cropping systems (wheat monoculture and wheat-faba bean rotation and three tillage management—conventional, reduced and no-tillage) on some chemical characteristics of SOM and their relationship with labile carbon in a Mediterranean semiarid environment revealed that SOM components and characteristics showed significant correlations with the soil biochemical parameters confirming the expected synergism between chemical and biochemical properties. The study demonstrated that (i) no-tillage and crop rotation improve the chemical and biochemical properties of SOM of vertisol and (ii) tillage management and cropping system after 19 years affected the chemical and biochemical properties of SOM more than its quantity (Laudicina et al. 2015; Layek et al. 2018; Meena et al. 2018c).

11.4.4 Green Manuring

Green manuring is one of the most beneficial practices and an alternative source to inorganic N fertilization. Mostly, the fast-growing legume green manures are used which have efficient nitrogen fixation. *Sesbania rostrata* at 75 days of growth or green gram incorporation recorded significantly higher microbial activity in terms of CO_2 evolution and dehydrogenase activity in soil and microbial biomass (Tilak et al. 1999). Inclusion of four green manure legumes crops (*Lens culinaris*, *Lathyrus tingitanus*, *Lathyrus sativus* and *Pisum sativum*) as partial fallow substitute gave average advantages of 385% in a number of bacteria, 210% in a number of fungi, 170% in microbial biomass, 191% in microbial biomass N, 202% in DHA, 171% in PHA and 287% in ASA compared to fallow-wheat system. The biomass C or N to total soil C or N, increased from 1.6 and 2.0% in fallow-wheat to 1.9 and 2.6% under continuous wheat and to an average of 2.4 and 3.5% under green manure-wheat systems indicating the beneficial effect of legumes on soil biological properties (Biederbeck et al. 2005; Meena et al. 2014; Yadav et al. 2017c). Addition of carbonaceous matter increased the GSA, PHA, UA and total organic carbon in comparison to unamended soil (Gopinath et al. 2009; Meena et al. 2015b). In another study, faba bean and vetch green manure residues increased bulk soil microbial biomass carbon or β-GSA activity more than the pulse crop residues in the first and third subsequent crops; soil microbial biomass and β-GSA were often positively correlated with initial crop residue N concentration and negatively correlated with initial C:N or C concentration (Lupwayi and Soon 2016). β-GSA was always greater in the fall after crop harvest than in summer, and β-GSA was a more sensitive and consistent biological indicator and perhaps soil health than MBC.

11.4.5 Inorganic Fertilizers

Fertilizers are an important input to supply plant nutrients in crop production. Balanced fertilization in general promotes the biological properties. Addition of only nitrogen or nitrogen + phosphorus decreased the particulate organic matter and soil respiration and microbial biomass carbon and nitrogen, which, however, increased with the addition of nitrogen, phosphorus and potassium (NPK). The total viable bacterial numbers increased with the addition of fertilizers, and the highest population was found in treatment with recommended doses of NPK+ farmyard manure (Selvi et al. 2004). In the long-term fertility experiment, Bhatt et al. (2012) concluded that increasing levels of NPK increased the MBC and N and the activities of DHA and UA in the soil. However, there was differential behaviour on AM fungus species *Acaulospora* sp.1 which showed no change in spore number with fertilization, whereas *Entrophosphora schenckii*, *Glomus mosseae*, *Glomus* sp.1, *Scutellospora fulgida* showed a decline in absolute number in response to fertilization (Bhadalung et al. 2005). The maximum values of all the parameters were noticed with 100% recommended dose of NPK with 15 tonnes FYM. DHA increased with the balanced application of nutrients which is resultant of oxidative activity of soil microflora. However, DHA activity is not a reliable index of microbial activity for soils receiving high nitrogen input. The treatments receiving high rates of N either as chemical fertilizers alone or in combination with organics and N fertilized wheat cropping system have visualized high UA (Pajares et al. 2011; Meena and Yadav 2015).

Long-term application of excessive chemical fertilizers has resulted in the degeneration of soil quality parameters such as microbial biomass, communities and nutrient content, which in turn affects crop growth, productivity and sustainable productivity. Adding manure compost significantly increased the number of cultivable microorganisms and MBC and thus enhanced soil respiration and enzyme activities, whereas nitrogen fertilizer treatments decreased the MBC and enzyme activities (Zhen et al. 2014). Integrated nutrient management in French bean significantly increased the PHA, UA, microbial respiration and MBC in an acid Alfisol of Himachal Pradesh (India) as reported by Datt et al. (2013) over alone application of chemical fertilizers. Nitrogen fertilization affected the rate of SOC decomposition by regulating extracellular enzyme activities (Jian et al. 2016; Ram and Meena 2014). The study revealed that N fertilization significantly increased the cellobiase activity, carbon acquisition, acid PHA, β-1,4-xylosidase, β-1,4-GSA, α-1,4-GSA and UA by 6.4, 9.1, 10.6, 11.0, 11.2, 12.0, and 18.6% but decreased PERA, POA by 6.4, 7.9, and 11.1%, respectively. The study further revealed that N fertilization enhanced SOC and soil nitrogen by 7.6% and 15.3%, respectively, but inhibited MBC by 9.5%. Significant positive correlations were found only between response ratios of acid phosphatase; MBC and total nitrogen showed unidirectional trends under different edaphic, environmental and physiological conditions. The study provided the first comprehensive set of evidence that low hydrolase and oxidase activities respond to N fertilization in various ecosystems.

11.4.6 Integrated Pest Management

Pests are an integral component of crop production, and different chemicals are used to control them. Pests and diseases reduce crop biomass production leading to less return of organic matter into soil through root biomass. Although certain pesticides are not applied to the soil, it is an eventual sink in one or other way. Most pesticides are applied at rates approximately those used in field applications causing only slight change in population and activities of microorganisms; however, soil microorganisms are affected adversely at high rates of application. A variable stimulatory effect of four herbicides on the population of non-symbiotic N_2 fixers in the rhizosphere of rice has been studied by Debnath et al. (2002). They reported that oxyfluorfen has more stimulatory effect in comparison with butachlor and oxadiazon. Soil application of herbicide metribuzin @2.5 kg ha^{-1} enhanced the release of ammoniacal nitrogen up to the 5th week. However, it decreased the nitrate content in soil at different intervals indicating sensitivity of nitrifying bacteria to application of metribuzin. Similarly, Srinivasulu et al. (2012) found that the population of *Azospirillum* sp. and rate of ammonification increased at particular concentrations

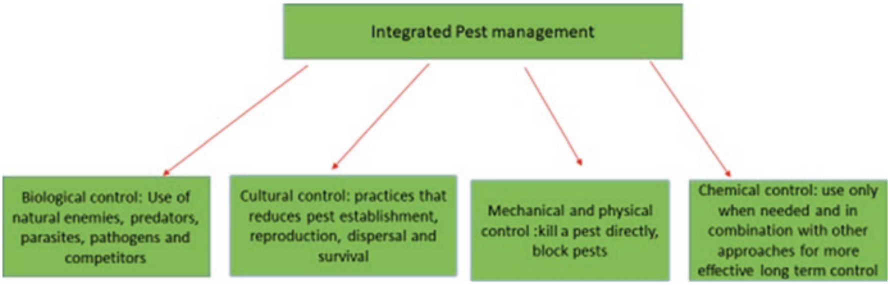

Fig. 11.3 Various integrated pest management approaches

of pesticides (i.e., 2.5–5.0 kg ha^{-1}) due to synergistic and additive interaction between pesticides and microorganisms, but at higher concentrations (7.5 and 10.0 kg ha^{-1}), the pesticides exerted antagonistic interactions on the population of *Azospirillum* sp. and ammonification (Fig. 11.3).

11.5 Soil Enzymes and Yield Sustainability

Several attempts have been made to show soil enzyme activity-fertility-crop productivity relationships, but strong correlations can be expected only in unmanaged ecosystems or low-input agricultural systems because, in managed systems, other factors may confound or override the relationship between soil biological activity and plant productivity. With respect to soil quality, strong negative relationships have been found between enzyme activity and soil bulk density and positive relationship with water infiltration (Martens et al. 1992). Alternative systems involving legume green manures had improved soil structure and enzyme activity (Boltan et al. 1985) as compared to conventional systems. Increased activities of several enzymes have been shown with organic amendments, green manure/crop residues (Rao and Pathak 1996) and municipal refuse. Cultivation depresses enzymatic activity (Gupta and Germida 1988). Majority of studies have reported significant correlation between soil enzymes and plant yield, whereas some studies show no close relationship. For example, mean grain yield of different crops under rain-fed production systems was positively correlated with DHA, ASA and UA in soil (Mandal et al. 2007; Varma et al. 2017b).

Grain yields of groundnut-finger millet, finger millet monocropping, winter sorghum, soybean and upland rice were significantly and positively correlated with DHA, ASA and UA, whereas there was no positive correlation with groundnut monocropping and pearl millet (Saha et al. 2008). The reason attributed was that the latter two cropping systems were practiced under semiarid conditions with low rainfall and high mean annual temperatures as compared with other five systems. The sustainable yield index was also positively correlated with all the three enzymes in all production systems except in soybean. However, under irrigated maize-wheat-cowpea system, Manjaiah and Singh (2001) reported significant correlation between yields and all the enzymes studied. Similarly, using linear regression models, Lopes et al. (2013) interpreted the enzymatic activities cellulase (CA), β-GSA, acid PHA and ASA as a function of the relative cumulative yields of corn and soybean. The plant productivity is under the influence of many factors like soil quality, plant genotype, biotic and abiotic stresses, etc. Further, in managed ecosystems, many other factors may influence the relationship between enzyme activity and plant productivity.

11.6 Soil Enzymes and Climate Change

Increasing atmospheric concentrations of CO_2 and other greenhouse gases is resulting in global warming. The soil enzyme activities are affected by abiotic (e.g. temperature, water potential, and pH) and biotic (e.g. enzyme synthesis and secretion) factors. Climate change-induced extreme weather conditions are affecting agriculture and hence can affect the quality and quantity of soil enzymatic activity. These changes will have important consequences for ecosystem functions such as decomposition, nutrient cycling and plant-microbe interactions, which will ultimately influence productivity and net C balance. The impact of climate on microbes and their extracellular enzymes, although of profound importance, is not well understood but may be predicted, assessed and managed (Burns et al. 2013; Steinweg et al. 2013; Meena et al. 2017c).

Growing concern about the potential consequences of climate change on soil processes, coupled with the desire to develop methods for improving C sequestration, has stimulated experimental research, modelling and theorizing (Burns et al. 2013). Elevated atmospheric concentrations of CO_2 may affect soil microbial communities directly or indirectly. Increased plant rhizodeposition, water use efficiency and increased nutrient uptake under elevated atmospheric CO_2 strongly affect microbial activities. Enhanced activities of oxidative enzymes (degrade resistant SOM) and enzymes involved in N and P mineralization (chitinases, peptidases (PEPA) and PHA) have been observed in response to elevated CO_2, whereas no response or decreased activity observed for C-degrading enzymes indicated the influence of CO_2 on microbial responses associated with C-, N-, and P-cycling (Kelley et al. 2011; Burns et al. 2013). Thus, the labile substrate additions through increased rhizodeposition can stimulate the decomposition of more resistant SOM due to extracellular enzymatic activity. However, effects may vary in different ecosystems. For example, in peatlands where the substrate is not a limiting factor, low O_2 availability and low pH restrict activities of oxidative enzymes (POA and PERA) leading to accumulation of phenols that inhibit hydrolytic activity and microbial substrate utilization. This, in turn, contributes to organic matter accumulation. On the other hand, in the substrate-limited arid system, photo-degradation of surface litter reduce soil input, low redox potentials of phenols due to alkaline pH, and active oxidative enzymes due to arid condition lead to increased decomposition of recalcitrant C compounds (Burns et al. 2013; Varma et al. 2017a). Biochar (which is stable C source) addition decreased the CO_2 emission in the atmosphere in comparison to application of farm yard manure and vermicompost. Sarma et al. (2017)

reported higher activities of UA, PHA, DHA and carbon mineralization till 60 days of incubation with the application of farmyard manure (FYM) and vermicompost as compared to biochar thus concluding that addition of biochar in acid soil would be a sustainable option to reduce the C mineralization which also maintains nutrient status of sandy loam soil of northeast India.

Available studies suggest that warming effects could be either positive or negative depending on the nature and kinetics of the target enzyme being assayed. A study in the Mediterranean indicated that urease and β-GSA were positively correlated with soil temperatures in winter and negatively in summer. Warming increased soil enzyme activities in winter (when soil moisture was highest) and in spring (Sardens et al. 2012).

Steinweg et al. (2013) studied difference among seasons and treatments in mass-specific enzyme activity indicating that enzyme production was not directly controlled by size and activity of microbial biomass. Mass-specific enzyme activity increased with an increase in temperature from low to medium and declined at a higher temperature, indicating that enzyme production increased with temperature or turnover rate decreased. Generally, the enzyme activity increases with temperature (up to some optimum), and so least theoretically the rate of enzymatically catalysed reactions will increase due to warming, assuming that enzyme pool remains constant (Burns et al. 2013). Contrary to this, warming may also increase enzyme denaturation rates and the activity of extracellular proteases which would contract any changes in enzyme pool sizes. Warming increased PHA (35.8%) but decreased CA (30%) in grassland ecosystem (Gong et al. 2015). In addition, warming caused a reduction in soil C (7.2%) and available P (20.5%). Further significant interactive effects of warming and N addition on soil enzyme activity indicated that global change may alter nutrient cycling by affecting soil enzyme activity.

Variations in seasonal precipitation may increase drying/wetting processes in soil. The diffusion of enzymes, substrate and reaction products in soil depends on soil texture and moisture. Under low moist conditions, in situ enzyme activities are low although in some microsites where solute concentration increases with pore spaces may exhibit high activity. Prolonged droughts are likely to decrease enzyme production resulting in low measured activities. However slower enzyme turnover in dry soils, along with continuous production, could lead to an increase in pool size during a drought (Burns et al. 2013; Steinweg et al. 2013). Rewetting leads to increased availability of organic matter which may result in a pulse of microbial biomass turnover thus causing a temporary increase in extracellular enzyme activities. On the other hand, decreased microbial biomass could lead to a decrease in enzyme production and a decline in the relative abundance of different types of enzymes, whereas under prolonged precipitation, enhanced plant growth and rhizodeposition resulted in enhanced enzymatic activities. The complexity of interactions between different climatic factors and soil properties makes it difficult to conclude the effect of a single abiotic factor on a particular soil enzyme (Steinweg et al. 2013). As soil enzyme plays an important role in nutrient cycling, all the climate change studies must consider soil enzyme activities as an important parameter while quantifying the outcomes of climate change.

11.7 Soil Fauna in Relation to Soil Enzyme Activity

In the present context, soil fauna as indicators of soil health is gaining importance. The invertebrate community supplies pre-transformed organic material to the microorganisms after fragmentation. Besides increasing the contact surface, the fauna helps in bioturbation of litter and also contribute to soil enzymes. The most representative organisms normally studied as indicators of soil health belong to soil mesofauna, which lives in the soil macro-pores and spaces in the soil-litter interface, feeding on fungal hyphae and organic matter and thus taking part in nutrient cycling and soil aggregation. The macrofauna includes bigger soil organisms which sometimes are active in soil functioning. Numerous studies are available on the effects of soil fauna on soil health parameters; however, some studies emphasize the effect of soil fauna on soil enzymes (Cardoso et al. 2013).

An increase in INV, PROA (during rice and wheat cultivation) and alkaline PHA (during rice cultivation) was observed in the presence of earthworms when maize was used as residue, whereas no change in DHA was observed in the presence of earthworms. The earthworm casts showed the significantly higher activity of five enzymes than in the surrounding soil possibly due to enhanced degradation of maize residues by earthworm which increased substrate concentrations in soil resulting in high microbial activity (Tao et al. 2009). The functional role of soil fauna is affected by feeding habit and the physicochemical properties of plant litter (Mukhopadhyay et al. 2014). They compared the feeding impact of *Anoplodesmus saussurii* (Humbert) feeding on semi-liquid portions and *Porcellio laevis* (Latreille) feeding by scrapping soft tissues, on litter breakdown and soil enzyme activities on decomposing leaf litter of two forest tree species, *Cassia siamea* (litter high in soluble carbohydrates, cellulose, and hemicelluloses) and *Shorea robusta* (litter high in polyphenols, tannin and lignin) in microcosms. Feeding by *A. saussurii* and *P. laevis* caused significant weight loss and decline of main chemical constituents in *C. siamea* litter, whereas the weight loss was much low in *S. robusta*. Soil enzyme activities were influenced by litter quality, with *C. siamea* litter exhibiting higher AMY, CA and INV activities than *S. robusta* litter. Soil enzyme activities were also affected by the presence of detritivores. Amylase activity increased in the presence of both arthropods in *C. siamea* and *S. robusta* litters. Further, the positive effect of *A. saussurii* was greater than that of *P. laevis* for all the enzymes in *S. robusta* litter. The results showed a direct and species-specific comminuting effect of detritivore arthropods on soil enzyme activities. Species-specific fungal enzymatic responses have been recorded in soil by Crowther et al. 2012. Lignocellulolytic enzyme production by saprotrophic basidiomycetes colonizing leaf litter increased during macrofauna and collembolan activity. This may be attributed to litter comminution and to fungal physiological responses to feeding. *Hypholoma fasciculare* and *Phanerochaete velutina* (exhibiting fast and extensive growth) increased production of cellulolytic and phosphorolytic enzymes during macroinvertebrate grazing, whereas the slow-growing species, *Rhizoctonia bicolor*, reduced enzyme production. Contrasting enzymatic responses of fungal species suggest the impact of soil fauna on fungal-mediated nutrient mineralization. However, a meta-analysis of litter box experiment (Frouz et al. 2015; Meena and

Yadav 2014) showed that the soil fauna significantly increased litter removal from the litter layer but did not significantly affect overall C mineralization. The rate of leaf litter decomposition is significantly faster than the decomposition of macrofauna faeces produced from the same litter. This suggests that larger litter mass loss from soil surface caused by soil fauna may be decoupled from the overall litter mineralization. Fauna effect of litter decomposition and mineralization is likely to be affected not only by climatic condition and litter quality but also by diversity and functional complexity of soil food webs as well as the time for which soil gets exposed to soil fauna. Several studies suggested that long-term fauna effect is more likely to promote C sequestration than mineralization. However, more studies are required on the role of soil fauna in organic matter decomposition.

11.8 Future Outlook for Study on Soil Enzymes

It has now been realized that the solutions to some of the problems created due to the intensive farming lies on adopting farming practices that conserve soil organisms and their diversity. Available literature indicates the loss in soil biodiversity and its functioning in different management practices. In order to obtain benefits of soil organisms for sustainability, a better understanding of the linkages among soil organisms, biological processes, soil physical and chemical and biological properties, ecosystem functions and the impact of the human intervention is required. More studies are required for developing linkage between soil enzymatic activity with crop yield, soil fertility, biological properties and physical and chemical properties as influenced by location and agro-climatic conditions. With the development of advanced techniques for molecular level, measurement of soil enzymatic activity has become possible up to functional microbial communities, gene, transcriptome and protein levels. The limitations associated with in situ enzyme activity need to be addressed to make the measurement more precise and practically feasible. Soil enzyme profiling under different cropping systems and management practices can help in developing a correlation between soil enzymatic activities, productivity and soil health of the ecosystem. Climate change-induced abiotic and biotic stresses influence soil enzyme activities. However basic and strategic research has to be conducted across agro-ecological regions to understand the dynamics of soil enzyme activities associated with cropping system and agro-techniques under changing climatic conditions.

11.9 Conclusion

1. Soil enzymatic activities were affected positively with crop rotation and addition of organic matter. Legume-based cropping proved superior over monoculture and cereal-based cropping.
2. Conservation tillage was found better than conventional tillage in affecting soil enzymatic activities and organic matter components and showed significant positive correlation with biochemical properties.

3. Green manuring improved microbial biomass and enzymatic activities. Balanced fertilizer application along with farmyard increased enzymatic activities.
4. The microbial population and enzymatic activities increased at particular concentration of pesticides; however, pesticides exerted antagonistic interactions on microbial population and ammonification at higher concentrations.
5. Majority of studies have revealed significant correlation between soil enzymes and plant yield. For example, mean grain yield of different crops under rain-fed production systems was positively correlated with DHA, ASA and UA in soil**.** However, plant productivity is under the influence of many factors like soil quality, plant genotypes, biotic and abiotic stresses, etc.

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