Anandkumar Naorem
Deepesh Machiwal *Editors*

# Enhancing Resilience of Dryland Agriculture Under Changing Climate

## Interdisciplinary and Convergence Approaches

Springer

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*Dedicated to my parents*
*Naorem Jyotinkumar Singh and Naorem Sobita Devi*

# Preface

This book on *Enhancing Resilience of Dryland Agriculture Under Changing Climate/Interdisciplinary and Convergence Approaches* covers six broad disciplines of agricultural management practices that are globally adopted to enhance resilience of drylands, which include (i) management of natural resources, (ii) improving sustainability of dryland farming systems, (iii) crop improvement and pest management, (iv) livestock production and management, (v) improving livelihood and socio-economic status of dryland farmers, and (vi) farm mechanization in dryland agriculture. In order to tackle the climate-induced risks of dryland agriculture, recent research studies have evolved advanced technologies and management strategies considering interdisciplinary and convergence approaches that integrate knowledge from multi-disciplines. However, a large number of such advanced management strategies are confined up to the research papers where detailed procedures of applying the advanced practices adapted to climate change for the management of dryland agriculture are not adequately dealt. It is revealed from the literature that a book systematically describing the advanced climate-resilient management practices along with their successful applications in dryland agriculture is not available. This book is an attempt to bridge this gap by unravelling controversies and characteristics of dryland ecosystems under the changing climate and describing management practices based on interdisciplinary and convergence science approaches. This may be called a reference book but not a textbook, and hence, this may not meet any curriculum entirely. However, a large portion of the information provided in the book may be useful to master's and doctoral students of agricultural science and engineering who carry out their research work as part of their degree. We are grateful for the support of the institutions and individuals who have cooperated with us. Their efforts and engagement have made this edited book possible.

Jodhpur, India

Anandkumar Naorem
Deepesh Machiwal

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**Anandkumar Naorem** works as a scientist in ICAR-Central Arid Zone Research Institute, Jodhpur, India. He was the former Head-in-charge in ICAR-CAZRI, RRS-Bhuj, India. He received his bachelor's degree from Assam Agricultural University, Assam, India, and his master's degree in soil microbiology and bioformulation from the College of Post-Graduate Studies, Central Agricultural University, Meghalaya, India. His doctoral dissertation at Bidhan Chandra Krishi Viswavidyalaya, West Bengal, India, focused on soil heavy metal remediation for safe cultivation of crops. He has published more than 25 national and international articles that have been peer-reviewed and has been awarded the best oral and poster presentations at numerous international seminars, workshops, and conferences. He received multiple national honours, including the 2015 Best Zonal Master's Thesis from the Indian Society of Soil Science. In addition, he has been awarded the UGC-Maulana Azad National Fellowship for Minority Students (India). He has been a frequent guest on science and technology-related All India Radio programmes. He has been leading several institution research projects focusing on soil quality in arid areas and is the principal investigator of an international effort to promote spineless cactus as dryland feed in arid regions of Gujarat.

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# Part I

# Dryland Agriculture and Climate Change

# Drylands: An Introduction

# 1

Anandkumar Naorem

## Abstract

A lot of research has been conducted worldwide to find out best management practices for nurturing dryland agriculture, and, consequently, a variety of technological options exist in literature to deal with the customary problems of dryland agriculture. However, it is observed that most of the available technologies individually address one issue of dryland agriculture at a time using knowledge of a particular discipline. It is further learnt that the climate change and global warming have profound repercussions for increasing frequency, severity, and duration of droughts and/or floods, which may have implications for future productivity of dryland agriculture including more water shortages or abundances and high or low runoff rates, diminished crop yields, and reduced water productivity. In the context of a growing global population and shifting weather patterns, reducing yield gaps in dryland agriculture is essential to meeting the world's food demand. Other goals, such as improving the nutritional content of food and stabilising crop yields over time, are also important within this framework. Ecological intensification may aid in meeting such needs in drylands by decreasing soil degradation, boosting soil C storage and water retention, and integrating soil N availability with crop N requirements. Multiple agroecosystem services could be gained through conservation agriculture and intercropping in dry environments, but more research is required to figure out how to manage farms on a local level so as to maximise their potential benefits.

## Keywords

Crop diversification · Crop yield · Ecosystem services · Intercropping · Yield gap

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## 1.1 Drylands under a Climate-Changing Scenario

As the average global maximum temperature has been rising, it is clear that climate change is occurring and has already had noticeable effects in many places of the world. For example, in India, maize and sorghum yields in Nalgonda District, Andhra Pradesh, and Parbhani District, Maharashtra, have decreased over the last few years due to a rise in temperatures (Jat et al. 2012). Throughout the world, farmers are already experiencing the effects of climate change. Climate change has been blamed for the recent famine in Eastern Africa, which has affected Somalia, Kenya, and Ethiopia. For the third year in a row, inadequate rainfall has caused crop failures in several countries, triggering starvation and mass migration to neighbouring countries. Southern Africa and Western Africa are also showing signs of a changing climate, especially in terms of rising temperatures (New et al. 2006).

About 38% of the world's human population resides in drylands, which are defined as regions with an aridity index (the ratio between average annual precipitation and potential evapotranspiration) ranging from 0.05 to 0.65 (Plaza-Bonilla et al. 2015). Drylands account for about 41% of Earth's land surface (Lal 2004). Nearly three-quarters of the continent of Africa is made up of drylands, making it the continent with the highest percentage of such areas in the world (Chimwamurombe and Mataranyika 2021). One of the world's most significant dryland agricultural regions is South Asia. One-fourth of the world's population lives in this region, which occupies only around 3% of the Earth's total land area. Temperature increases caused by climate change are having a devastating effect on the area. The World Bank estimates show that if no measures are taken to reduce C emissions, average annual temperatures in the region will rise by 1.5–3 °C (hotspot) by 2050, compared to 1981–2010 (Hoegh-Guldberg et al. 2018). As a result, this hotspot has the potential to reduce crop yields and decrease agricultural production, thereby threatening food security for half of the world's population. Smallholder and subsistence farmers in the Indo-Gangetic Plain, in particular, would be hit harder by rising temperatures than larger farms because of their limited ability to adapt (Kumar et al. 2020). Future food security will become an increasingly pressing issue as a result of the significant influence that these extreme climatic occurrences will have on food production. The United Nations' Sustainable Development Goals (SDGs) prioritise ensuring a reliable supply of safe and nutritious food for all people by 2030 (Tamburino et al. 2020). Current crop production in drylands is no longer viable due to the changing climate scenario, the need to feed the growing population, and a severely depleted resource base (land and water). Sustainable food provision for a large population will require the development of appropriate long-term coping methods for dryland agriculture. In drylands, the yield gap (the difference between the potential and actual output) is still quite large, especially in the case of rainfed farming. Although the Green Revolution of the second part of the twentieth century greatly aided in narrowing this gap, it also came with substantial environmental repercussions due to the increasing use of synthetic fertilisers and pesticides. Closing the yield gap in a climate change scenario presents a formidable obstacle for modern dryland agriculture, which must do so without significantly increasing the area farmed, which would have a negative impact on both ecosystems and biodiversity. In this line, it is important to assess a wide range of solutions, from ecological intensification to land-saving methods like increased cropping density and genetic improvement.

## 1.2 Challenges in Dryland Agriculture

The expansion of arid and semiarid regions poses a significant difficulty for the inhabitants of these regions. Due to climate constraints, the soils in these regions contain a naturally low soil organic carbon stock (C). Instead, they have a high concentration of inorganic C, of a stable form, primarily in the form of soil carbonates (Denef et al. 2008). Approximately 13–24 Pg C has been lost in grasslands and drylands due to poor management practises like intensive tillage, overgrazing, and the removal of vegetative cover, resulting in significant degradation processes like soil erosion, the loss of ecosystem services, and increasing rate of desertification (Zika and Erb 2009). Increasing human population pressure and the effects of climate change on hydrological regimes and net primary output are two of the new threats to the world's drylands (Mouat and Lancaster 2008). Soil erosion is common in arid regions due to a combination of factors, including a lack of soil cover, heavy storms (common in some arid regions, like the Mediterranean basin), weak soil structural stability (usually associated with low levels of soil organic carbon), and increasing human pressure. Soil erosion in drylands is exacerbated by several variables, including the presence of steep slopes. Furthermore, estimates indicate that erosion rates could increase by 25–55% in the twenty-first century as a result of climate change (Delgado et al. 2013). In turn, soil erosion can expose carbonates to weathering and acid deposition, both of which can accelerate the release of carbon dioxide from soils into the air. Soil erosion is common in arid regions due to a combination of factors, including a lack of soil cover, heavy storms (common in some arid regions, like the Mediterranean basin), weak soil structural stability (usually associated with low levels of soil organic carbon), and increasing human pressure.

According to Rapport et al. (1985), the term "Ecosystem Distress Syndrome" (EDS) refers to a variety of unfavourable outcomes that are connected with ecosystems that are experiencing some form of stress. The presence of several of these effects is readily apparent in regions where dryland salinity, a severe type of environmental degradation, has taken hold. One of the most consequential results of EDS is a shift in the disease prevalence seen in the plant, animal, and human populations. This occurs as the structure of the ecosystem begins to degrade, and the natural buffering and protective systems become ineffective (Rapport et al. 1985). Even though people have, to a certain extent, established technical and cultural buffers against environmental change, our well-being and survival are ultimately dependent on ecosystems that are working as they should (Rapport 2002). Soil dryness or drought is a major contributor to the production of aerosolised dust, which has been linked to negative effects on respiratory health (Nordstrom and Hotta 2004). However, some soils impacted by dryland salinity can be at higher vulnerability to wind erosion due to a reduction in plant cover and an increase in bare earth exposure, depending on soil type and the severity of salinity and waterlogging (Qadir and Schubert 2002). Aerosolising soil particles and bacteria can cause major health issues, and the combination of agricultural land practices, a seasonally arid environment, and soil deterioration and vegetation loss due to dryland salt creates ideal conditions for this to happen.

The grassland environment serves as a habitat for a diverse range of plant and animal species (Dlamini et al. 2014). As land degrades, there will be many problems for dryland farmers to solve. One evident result is a decline in animal and plant species diversity (Pacheco et al. 2018). The decrease in soil organic carbon and nitrogen content is a long-term effect of land degradation that has a negative impact on soil fertility. Vegetation abundance and biodiversity are both negatively impacted by declining soil fertility (Dlamini et al. 2014). Anthropogenic activities like overgrazing by animals, poor farming techniques, and deforestation can lead to a loss of biodiversity. Because of its potential impact on the reproductive cycle, climate change may also contribute to biodiversity loss. Furthermore, as the climate changes, some species may move to new habitats, seeking out more favourable weather conditions. Ecosystems and wildlife in the area will suffer as a result of this.

Most dryland farmers still employ old practices, which has undermined their ability to meet the food security needs of a growing population (O'Callaghan 2016). The farming techniques only allow for a limited harvest. However, unfamiliar procedures are a major reason why subsistence farmers don't use them (Ebrahimi Sarcheshmeh et al. 2018). It is not usual practice for farmers in rural Africa to employ microbially enhanced seeds or improved varieties (Kassie et al. 2011). Both stress tolerance and productivity could benefit from these developments. However, most rural farmers lack the resources necessary to make effective use of them (e.g. access to relevant information and services) (Rehman et al. 2017).

## 1.3 Management of Drylands for Sustainable Agriculture

Ecological intensification involves the substitution of on-farm methods that optimise yield-enhancing ecosystem services for conventional agricultural inputs like inorganic fertiliser. Mixed cropping, shifting planting dates and variety selection, and other forms of income diversification have long been used by farmers and others to adapt to climate challenges. Such measures, along with future technologies to deal with climate change, will need to be addressed in the future. Soils in dryland areas have an enormous potential to sequester C provided the right management and land-use policies are implemented within an ecological intensification framework, notwithstanding the constraints and bleak prospects (Naorem et al. 2022). The importance of vegetative covers in preventing soil erosion and maintaining soil organic carbon (SOC) in dryland areas has been known for a long time. Conventional management practises, however, impede the presence of adequate soil surface protection in these regions due to the following reasons:

Intensive tillage in herbaceous and tree crops.
Feed needs for animal production.
Excessive grazing.
The high feedstock demand for bioenergy.

Water scarcity is the principal limiting factor for crop diversification, net primary production, soil organic carbon dynamics, and soil microbial activity in dryland agroecosystems. Optimising the components of the soil water balance is the first principle of water conservation in plant production. Two unique management periods exist. The first is the window of opportunity for rain storage between crop harvest and planting. Strategies for managing soil and water during this time should prioritise increasing the amount of water stored in the soil to better adapt to the semiarid climate. The second cycle of management consists from planting and till harvesting the crop.

Increased productivity, more beneficial ecosystem services, and higher SOC can be achieved in dryland agriculture by focusing on the following four factors: increasing our understanding of the role of soil biology in C cycling, utilising plant diversity (legumes, agroforestry), implementing effective crop residue management, and settling on the optimal amount of ecological agricultural intensification (i.e. rotations, fertilisation, etc.). The water deficit caused by the imbalance between precipitation and potential evapotranspiration reduces the efficiency of dryland agricultural systems. Given the variability of precipitation in most dryland regions, there is an urgent need to provide regional decision tools for determining the best crop to grow, when to plant it, how much nitrogen to apply, and other agricultural management measures based on soil moisture. If the right choices were put into action, biomass production and SOC sequestration might both increase. It is important to focus on water retention after the water has penetrated the soil profile. It is crucial to keep the soil top covered in dryland areas so that water is not lost. There have been several suggestions for cropping techniques that may improve soil water retention. To improve soil water content, N availability, and weed control in dryland environments, fallow has traditionally been used. One of the most promising strategies to increase SOC stocks in dryland areas is the implementation of conservation tillage practices, such as reduced or no-tillage. These practices increase soil water storage, which in turn increases biomass production and C protection within soil aggregates.

When it comes to increasing C sequestration in soils, the availability of soil water for plants is crucial in dryland regions. This can only be accomplished by eliminating or greatly reducing the frequency of soil tillage and the duration of time that fields lie fallow. Pittelkow et al. (2015) observed that the only biome in which the combined application of all three conservation agriculture (CA) components boosted crop yield (by as much as 7.3%) was drylands. The reanalysis of these data showed that the aridity index correlated negatively with the effect magnitude of CA on crop yield.

Pittelkow et al. (2015) did not find any yield benefit from CA in dryland sites under irrigation, even though it is difficult to disentangle the mechanisms behind the treatment effect sizes in meta-analysis. The yield gains of CA under rainfed conditions in dryland sites may be due to increased water infiltration and soil moisture conservation. In dryland agricultural fields under CA, higher soil C accumulation and N retention were found (Plaza-Bonilla et al. 2015); however, these effects have not yet been linked to improvements in crop yield, suggesting that this is a topic worthy of further study.

Grazing can impact soil carbon in a number of ways, including soil compaction, a decrease in standing biomass, a reduction of vegetation cover, a change in root biomass, and possibly an increase in erosive processes. The influence of grazing intensity on SOC has been studied with varying results. Some researchers have discovered an increase in SOC stock with intensively managed grasslands (Reeder et al. 2004), while others have found that high stocking rates decrease soil C stocks by lowering the aboveground grass biomass, which in turn affects the more labile fractions (Smith et al. 2014). In a semiarid continental steppe in northern Inner Mongolia, Han et al. (2008) found that SOC and total N (0–30 cm depth), respectively, decreased by 33% and 24% under heavy grazing compared to light grazing. Steffens et al. (2008) verified these findings by observing a reduction in a variety of soil characteristics, including organic carbon, in a heavily grazed grassland in the same semiarid region. Soil drying could be exacerbated by climate change's effect on surface temperatures. This is particularly important in dryland agroecosystems, where a lack of water in the soil is the primary constraint on C dynamics. Soil water scarcity may come from the warming effect on soil water content, along with the general decrease in precipitation expected by climate models for dryland areas. Li et al. (2015) demonstrated the effect of drought on soil C by estimating a loss of 0.46 Pg C in Central Asian drylands throughout the decade-long drought period from 1998 to 2008, which may have been caused by prolonged La Niña occurrences. Drying soil slows down breakdown of organic matter because of reduced microbial activity. Indeed, extremely low soil moisture levels may counteract the increased microbial activity that occurs in response to heat (Almagro et al. 2009).

It has been suggested that growing legumes as part of a crop rotation is one way to boost soil organic carbon in arid regions. As a result of their beneficial effects, legumes can decrease the amount of fertiliser required for succeeding crops. The risk of N leaching during fallow periods is increased by the faster mineralisation rate of leguminous crop residues, although most semiarid dryland systems provide few chances to apply cover crops. Moreover, the higher rate of breakdown that occurs after adding N-rich agricultural residues from legumes does not necessarily lead to increased SOC stocks. Furthermore, from a purely economic standpoint, using legumes in semiarid dryland crop rotations is not necessarily beneficial and may also result in increased N losses as $N_2O$. Benefits in crop yields can be obtained through intercropping by cultivating two or more crop species or genotypes together on the same plot of land (Vandermeer 2012). The negative consequences of plant competition may be outweighed by the positive effects of resource (e.g. water, N) efficiency and pest management (Brooker et al. 2015), making intercropping an effective tool for promoting ecological intensification of agriculture in drylands. This becomes especially clear when intercropping with legume species, which fix atmospheric N (Hauggaard-Nielsen and Jensen 2005). Alley cropping systems with N-fixing woody species and cereals are examples of the agroforestry methods that have a long history in drylands and should be considered as another way to improve plant diversification through intercropping. The goal here is to prevent the crop from competing with the trees, which means that the trees must have access to resources that the crop would not normally have access to. In order to counteract desertification and enhance soil C buildup while simultaneously increasing agricultural output, scientists have been actively studying this phenomenon in recent years. In the context of a growing global population and shifting weather patterns, reducing yield gaps in dryland agriculture is essential to meeting the world's food needs. Other goals, such as improving the nutritional content of food and stabilising crop yields over time, are also important within this framework. Ecological intensification in drylands may aid in meeting such demands by lowering soil degradation, raising soil C storage and water retention, and linking soil N availability to crop N needs. More study is needed to determine the best way to manage a farm's numerous functions on a local scale; however, conservation agriculture and intercropping have been advocated as a way to increase the benefits of arid system farms.

Droughts are extremely detrimental to agriculture, food security, and the economy. Agricultural practices must be managed during droughts or their aftereffects must be mitigated in order to mitigate the negative effects of droughts. Environmental rehabilitation is one such technique. Land rehabilitation seeks to counteract the impacts of land deterioration (Pacheco et al. 2018). This entails both behavioural and structural changes (Gebremeskel Haile et al. 2019). Planting trees on degraded land, often known as reforestation, can lead to a total reversal of damaged land. Alternately, enhanced natural regeneration resulting from the in situ planting of seeds may also be used (Pacheco et al. 2018). In locations with the severe occurrences of land degradation, it is vital that land restoration occurs. Nevertheless, prevention of land deterioration is preferable (Nkonya et al. 2016). There are increased risks of vector-borne diseases and food insecurity due to climate change (Thornton et al. 2014). Damage from frost and delayed flowering times could be brought on by early frosts and heavy rain. Soil organic matter breakdown slows very significantly during droughts (Reyer et al. 2013). The detrimental impacts on biological systems are enormous as a result of these shifts. As a result, it is crucial to adopt mitigation protocols to lessen the effects of climate change on agriculture. Haussmann et al. (2012) indicated few points that could help to serve this purpose such as producing seeds with genes that can withstand higher temperatures, enhancing farmers' ability to adjust to new conditions, refining breeding and selection procedures, and learning to better manage water resources.

## 1.4 Future Prospects in Dryland Agriculture

There is the potential for social and economic advantages to be derived from the soil in dryland areas, including improvements to the viability of agricultural systems, environmental restoration, and the reduction of poverty. At the local, regional, and global levels, there is abundant evidence indicating that increasing dryland carbon content is beneficial. These benefits include greater crop yield, improved agricultural sustainability, and mitigation of climate change. It is important to optimise livestock integration in dryland environments so that carbon and nitrogen cycles are integrated and the longer residence time of the carbon stored at depth is used to maximum effect. Improving ecosystem services requires more investigation into the relationships between soil biodiversity and C cycling. In addition, the study areas need to be expanded in order to more accurately describe the complex landscape processes that influence C sequestration and to gain a deeper understanding of the interactive impacts of management and global warming on C cycling in soils. Incentives for successful C management routes, such as increased knowledge at the farmer level and a tighter connection between environmental and social sciences, can be created with the help of supportive policy. Sequestering a sizable amount of carbon in dryland soils is possible, and doing so will have positive effects on the ecosystem and society.

Successful adaptation of dryland agriculture to climate change and variability requires the identification of climate-resilient crops and cultivars for various locales. Dimes et al. (2008) used APSIM simulations to determine that in semiarid regions of Zimbabwe, pigeon pea and sorghum were more tolerant to the climate change shocks than maize and groundnut, mostly as a result of an increased harvest index and increased water-use efficiency.

Adapting to climate change and variability may be possible for dryland agriculture if farmers choose to diversify their crop options by planting multipurpose tree species, medicinal and aromatic plants, etc. Households in model watersheds were able to produce both the food they needed and a surplus by increasing the intensity of their crop production and diversifying their crop selection to include high-value crops. Reusing the runoff water helps prevent flooding in downstream areas and protects crops from drought. Therefore, integrated watershed management will be crucial for preserving soil and water, making the most of rainwater, raising crop and livestock yields, and raising the overall standard of life, particularly in arid and semiarid regions. Crop productivity in dryland areas must be increased, and climate change resilience must be imparted through the promotion of effective soil, crop, nutrient, and pest and disease management methods because water alone is not enough to do so. One of the adaptation techniques for climate change is the use of harvested rainwater for supplemental irrigation, which can greatly aid in lowering the probability of crop failure and increasing output in dryland regions. Developing climate change mitigation and adaptation methods, as well as rebuilding the natural resource base, which is critically deteriorated in the drylands at present, is necessary since the drylands will become increasingly crucial to ensuring the food security of the nations in the future. Millions of the impoverished who reside in dry and semiarid areas will benefit greatly from this, as it will ensure their ability to make a living.

The use of radioactive isotopes in nuclear technology is promoted as a means to increase production. These are utilised as disease tracers and early detection tools. Agricultural institutions that are intended to support farmers in arid regions frequently fail to provide enough support. Research institutions receive inadequate funding and resources. Inadequate markets exacerbate the sector's profitability issues, posing a further difficulty (Nagaraj 2014). Among subsistence farmers in rural areas, commercial production is frequently reserved for the case of surplus produce. In the lack of formal connections, it is sometimes difficult to develop effective and competent market systems (Dixit et al. 2013). Thus, market linkages refer to local or global economic relations based on input or output (Matenga and Hichaambwa 2017).

The yield gaps in dryland agricultural systems can be identified, and solutions to reduce the gaps in yield under different scenarios can be suggested, using process-based mechanistic models. Lobell et al. (2009) studied the magnitude and cause of yield gaps across the globe and made similar recommendations about the use of tools. However, improving crop yields in isolation would not be enough to make these systems sustainable; instead, a total farm approach should be taken. In order to calculate the costs and gains of different farming methods, it is necessary to model agricultural systems. Small-scale dryland farmers in Kenya had their income and wealth estimated using econometric modelling and statistical matching (Ogada et al. 2020). Findings indicated that drought-resistant crop use coupled with livestock investment could be an effective adaptation strategy for coping with climate variability and change. There needs to be a shift in the direction of future research in order to achieve a long-term goal of eradicating hunger. Of the 570 million farms in the world, more than 475 million are less than 2 hectares in size, but most of our research has focused on larger farms without giving small farming the attention it deserves. Previous studies have generally drawn the erroneous conclusion that smallholders may adapt to climate change by implementing novel strategies such as increasing their production of climate-resilient crops through extension services. To fulfil SDG and put an end to hunger, however, it will be necessary to focus more of our future research on smallholder farms.

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# 2

# Current State and Prediction of Future Global Climate Change and Variability in Terms of $CO_2$ Levels and Temperature

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## Abstract

The long-term weather patterns that distinguish the different parts of the world are changing due to global climate change (CC). It is very real, as it is subject to various external forcing, both natural and anthropogenic. With the onset of the industrial revolution, the problem of Earth's climate was amplified manifold. Human activities, the use of fossil fuels in particular, have significantly warmed the planet by raising atmospheric concentrations of gases that trap heat. Among the GHGs, $CO_2$ is the single largest contributor toward global warming. From 1850–1900 to 2010–2019, the likely range of Earth's surface temperature (EST) and $CO_2$ increases by human activity is 1.07 °C and 40%, respectively. These could exert catastrophic effects on Earth's biodiversity, food security, water resources, marine and costal ecosystems, city infrastructure, human health, human migrations, and regional conflicts. In order to manage development opportunities and hazards, as well as for adaptation and mitigation, timely, actionable, and trustworthy climate prediction plays a critical role in decision-making for individual as well as industrial users and for national development planning. IPCC estimated that unmitigated human-led $CO_2$ emissions would be nearly two to three times higher than the current levels that would elevate the EST by 3.6–4.4 °C at the twenty-first century end. To combat the expected impacts of climate change, there is a need to adopt policy-driven mitigation (emission reductions) and adaptation (preparing for unavoidable consequences) strategies such as afforestation, carbon sequestration, climate-smart farming practices, renewable energy, environmental greening, etc.

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**Keywords**

Climate change · Drivers · Greenhouse gas emissions · Global warming · Representative Concentration Pathways · Shared Socioeconomic Pathways · Combat strategies

## 2.1 Introduction

The historic Toronto Conference declaration from 1988 stated that the possible effects of climate change (CC) could be "second only to a global nuclear war" (Kemp et al. 2022). Achieving the millennium development goals and reducing poverty will be significantly impacted by CC (IPCC 2013). Several factors such as water resources, crop production, food security, nutrition, and public health are all threatened by CC (Fitchett et al. 2016). However, various hard-won advancements implemented to meet these global goals can lessen or even reverse these dangers. Failure to address CC would lead to the spread of illness, supply-chain disputes, and economic system collapse, which will increase global instability in various aspects. The vast majority of climate scientists have confirmed that man-made activities are to blame for changes in the global climate (Fawzy et al. 2020). These include greenhouse gas-producing industrial operations including mining, deforestation, the production of petrochemicals and refineries, and the fossil fuel burning. The greenhouse effect traps the heat emitted from the Earth's surface, raising EST by around 30 °C (Akanwa et al. 2019). An annual 13 million hectares of forest are lost due to mining and agricultural operations (Akanwa et al. 2017). According to the 2018 report of "Intergovernmental Panel on Climate Change" (IPCC), if the emissions of greenhouse gases (GHG) are not decreased within the succeeding 30 years, the Earth would suffer disastrous impacts (IPCC 2018a). Around 63% of the global GHG emissions are produced by developing nations, yet 98% of those nations are severely impacted by CC (Javadinejad et al. 2019). The most dangerous effects of CC will be experienced by these nations, which also have the least ability to adapt their combat mechanisms.

In order to combat CC, mitigation (emission reductions) and adaptation (preparing for unavoidable consequences) are required (Rolnick et al. 2022). The adaptation should be considered as a key component of any effective plan to lessen the wide-ranging negative effects of CC. Complex relationships exist between adaptation and mitigation. Less adaptation is required if more mitigating measures are taken. However, despite the significant efforts made to reduce GHG emissions, some parts of CC are unavoidable and will result in unfavorable repercussions, some of which are already being felt (Settele et al. 2015). Therefore, in this present chapter, the present scenario of CC and its effect on altered $CO_2$ and temperature levels have been thoroughly discussed along with an address to the predicted future CC. The drivers and effects of CC have also been critically analyzed with a light on the combat strategies for the adverse CC impacts.

## 2.2 Concept of Climate Change (CC) and Climate Variability (CV)

IPCC defines "Climate change as a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcing such as modulations of the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use" (IPCC 2018b).

In line with IPCC, CC is the modification in climate over period, whether caused by natural variability or anthropogenic action. In contrast, the term "Climate Change" used by the "United Nations Framework Convention on Climate Change" (UNFCCC 2007) is different from this, referring to a shift in the climate that can directly or indirectly be connected to various human actions. This change affects both the natural climate variability found across comparable time periods and the composition of the Earth's atmosphere.

CC is the gradual change (increase or decrease) over long period in normal conditions (e.g., temperatures) or ranges of weather conditions (e.g., frequency as well as severity of extreme weather events (EWEs)). Unlike interannual variability, it progresses slowly and steadily, making it very difficult to see without a scientific record of statistical data on climate variables. This is due to both natural variability and human activity. It is caused by fluctuations in the Earth's atmosphere, for example, orbital deviations around the Sun and changes in the atmosphere caused by anthropogenic activity. There is no fundamental problem with CC. It has occurred in the past and will do so again in the future. The current problem arises from the speed of change. There is strong enough evidence that man-made activity is causing global warming at this extraordinary and unprecedented rate. Since the mid-twentieth century or pre-industrial times, anthropogenic measures such as fossil fuel burning and clearing land for intensive agriculture and industrialization have led to significant emissions of GHGs into the atmosphere, resulting in more heat energy absorbed and a higher surface temperature of the Earth (Fig. 2.1).

Climate variability (CV) has a harmful effect on agriculture and livelihoods compared to CC. Consistent with the IPCC, "Climate variability is defined as variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability)" (IPCC 2018b). Scientists believe that CV on seasonal, annual, or decadal timescales oscillates around long-term statistics of climate normality. This scenario can be split into two sections for easy understanding: average and range (Fig. 2.1). Calculating the range will give you a rough idea of the average and vice versa. So, both complement each other.

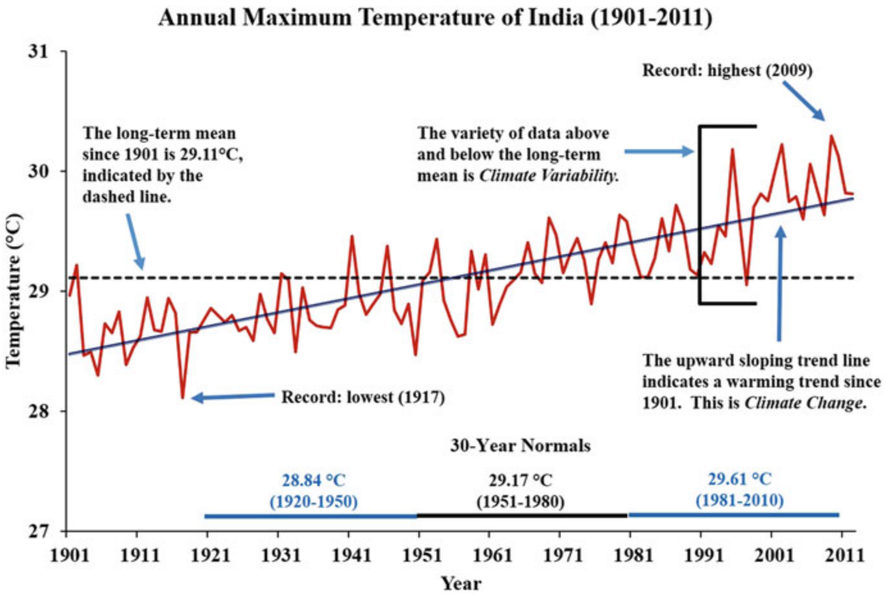

**Fig. 2.1** Long-term yearly maximum temperature for all of India (source: "https://data.gov.in/resources/annual-and-seasonal-maximum-temperature-india")

**Average** Climate is not defined by a specific time frame. However, to measure climate, scientists normally utilize mean weather conditions at 30-year intervals. These 30-year means, also known as climate normals, are used to study, monitor, or describe the climate (or a specific aspect of climate) of a particular area. It takes 30 years of data to compute an average that is unaffected by fluctuation from year to year.

**Range—The Variety** Averages only tell half the story of CC. Variation around the mean – the weather range – is the other half. When the average is calculated, it "smoothes" the diversity of the data it contains. But knowing this variety, particularly the extremes, can be quite beneficial.

## 2.3 Observed Changes in the Climate System

Scientists are detecting changes in climate in every region and across the entire climate system, according to IPCC. Numerous recorded CCs have not been seen in thousands, if not hundreds of thousands of years, and certain repercussions, such as the continuing rise in sea level, are already apparent. The magnitude of recent climate system-wide changes and the present state of its components are unparalleled in several centuries to many thousands of years.

Warming of the climate system is unequivocal, and many of the changes observed since the 1950s have not been observed before for centuries, even millennia. In addition to the warming of the ocean and atmosphere, there has been an increase in sea level and a decrease in snow and ice cover. There is no doubt that humans have influenced the climate system, and recent greenhouse gas emissions by anthropogenic activity are at an all-time high. Natural and human systems both have been significantly impacted by recent CC. Present status of $CO_2$ and other GHG emissions and global CC in terms of temperature, sea-level, EWEs are sited below (IPCC 2021, 2022).

### 2.3.1 Recent Developments and Current Trends in $CO_2$ and Other GHGs Emissions

The increase in concentrations of well-mixed greenhouse gas (WMGHG) observed since about 1750 is clearly caused by anthropogenic activity. The following are the status of recent developments and current trends in $CO_2$ and other GHGs that leads to CC:

- Since 2011, concentrations of GHGs in atmosphere have continued to rise, reaching annual means of 410 ppm, 1866 ppb, 332 ppb for $CO_2$, $CH_4$, and $N_2O$, respectively, in 2019. Over past six decades, the land and the sea have absorbed a fairly constant proportion of human-induced $CO_2$ emissions (around 56% annually globally), although this varies by region.
- Since 1750, $CO_2$, $CH_4$, and $N_2O$ concentrations have risen by 47%, 156%, and 23%, respectively. $CO_2$ levels (atmospheric) in 2019 were the highest than the last two million years, while $CH_4$ and $N_2O$ levels had not been that high in at least 800,000 years.
- In 2019, the total amount of net GHG emissions by anthropogenic activity was 59 ± 6.6 $GtCO_2$-eq, which was 54% (21 $GtCO_2$-eq) greater than it was in 1990 and 12% (6.5 $GtCO_2$-eq) higher than it was in 2010. The yearly average from 2010 to 2019 was 56 ± 6.0 $GtCO_2$-eq, which is higher than that of 2000 to 2009 by 9.1 $GtCO_2$-eq $year^{-1}$. It is the largest increase in average emissions over last decade. The average yearly growth rate slowed from 2.1% per annum in 2000–2009 to 1.3% per annum in 2010–2019 (Fig. 2.2).
- Since 1990, all significant GHGs have shown an increase in anthropogenic emissions, albeit at varying rates. While fluorinated gases experienced the highest relative growth beginning from low levels in 1990, $CO_2$ from fossil fuels and industries experienced the largest growth in absolute emissions by 2019 followed by $CH_4$.
- In 2019, the energy supply sector accounted for over 34% (20 $GtCO_2$-eq) of all GHG emissions (net) by anthropogenic activity, followed by industry (24%, 14 $GtCO_2$-eq); 22% from agricultural, forestry, and other land use (AFOLU) (13 $GtCO_2$-eq); 15% from transportation (8.7 $GtCO_2$-eq); and 6% from buildings (3.3 $GtCO_2$-eq).

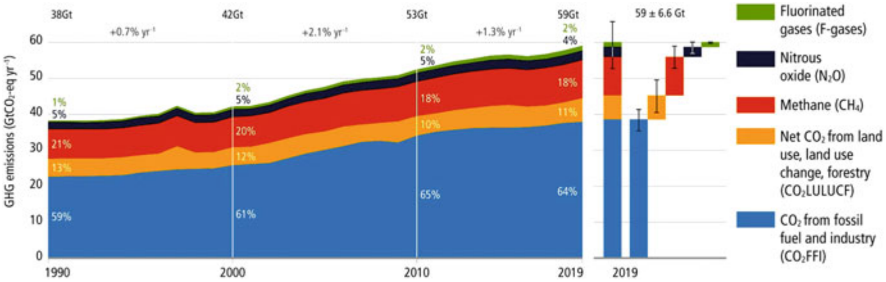

**Fig. 2.2** Global net anthropogenic GHG emissions 1990–2019

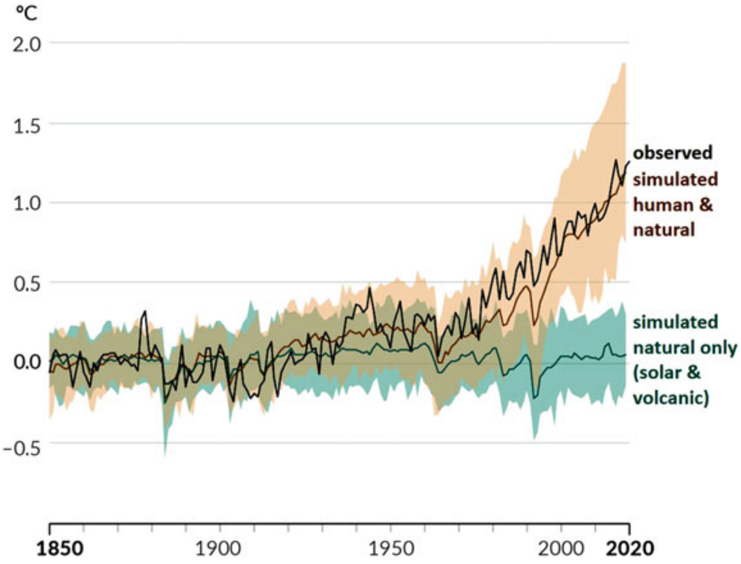

**Fig. 2.3** Change in average yearly global surface temperature as observed and simulated

## 2.3.2 Surface Temperature (ST)

The last four decades since 1850 have all been warmer than the decade preceding them (Fig. 2.3). The average global ST was 0.99 °C [0.84 to 1.10] higher between 1850 and 1900 than it was in the twenty-first century's first two decades (2001–2020). In comparison to 1850–1900, the global ST increased by 1.09 °C [0.95 to 1.20] between 2011 and 2020, with increases over land being higher (1.59 [1.34 to 1.83] °C) than that of ocean (0.88 °C [0.68 to 1.01]).

- From 1850–1900 to 2010–2019, the likely range of Earth's surface temperature increases by human actions is 0.8–1.3 °C, with 1.07 °C as a best estimate.

- The rise in average EST since 1970 has been quicker than any other 50-year period in last 2000 years. The temperatures of 2011–2020 (most recent decade) are higher than those of the most recent warm period (1850–1900) by 0.2 to 1 °C, which occurred about 6500 years ago and spanned many centuries.

### 2.3.3 Rise in Mean Sea Level (MSL)

The global MSL between 1901 and 2018 rose by 0.20 m (0.15 to 0.25 m). The average annual rate of MSL rise between 1901 and 1971was 1.3 (0.6 to 2.1) mm, rising to 1.9 (0.8 to 2.9) mm between 1971 and 2006 and then to 3.7 3.2 to 4.2] mm between 2006 and 2018.

### 2.3.4 Extreme Weather Events (EWEs)

Every part of the world is already experiencing the effects of human-led CC on a number of meteorological and climatic extremes.

- Since the 1950s, hot extremes, together with heatwaves, have risen in occurrence and strength across most land areas, while cold extremes decreased in frequency and intensity. Since the 1980s, the frequency of marine heatwaves has increased by around twofold.
- Since the 1950s over the majority of the land area, the intensity and occurrence of heavy precipitation have amplified, and human-led CC is likely the main driver ("main driver" means responsible for >50% of the change). Due to increasing land evapotranspiration, human-induced CC has made some places more prone to ecological and agricultural droughts.
- Over the past four decades, the frequency of major (Category 3–5) tropical cyclones has grown globally.

## 2.4 Emission Trends, Drivers, and Impacts of CC

### 2.4.1 Emission Trends and Drivers

GHGs raise Earth's average surface temperature by trapping outgoing long-wave radiation. Since industrial revolution, anthropogenic activities have led to emission of large quantity of GHGs, especially $CO_2$ into the atmosphere, leading to rapid rise in Earth's average surface temperature or global CC per se. Natural and anthropogenic factors which both trigger GHG emission that alters Earth's energy budget are drivers of CC (IPCC 2013), which in turn influence the Earth's climate. The strength of the drivers can be quantified in terms of radiative forcing (RF) that measures radiative imbalance (change in energy flux) in Earth's atmosphere following changes in these drivers over the industrial era. The RF, expressed in watts per square meter

($W\ m^{-2}$) is calculated either at the tropopause or at the top of the atmosphere (TOA) (approximately at 20 km altitude) (Myhre et al. 2013). Positive RF means near-surface warming while surface cooling regarded as negative RF (IPCC 2013). The drivers of CC can be categorized into (i) natural drivers and (ii) anthropogenic drivers.

#### 2.4.1.1 Natural Drivers

Scientists usually use indirect evidences or proxy measurements to determine pre-historical climate situations like data collected using ice cores, tree rings, soil boreholes, glacier lengths, ocean sediments, and pollen remains. Only a few significant drivers of changes existed before the industrial era that may be considered as natural causes of CC and are beyond any human control. These are changes in Earth's orbit (Milankovitch cycles), variations in solar irradiance (SI), and volcanic eruptions. Changes in Earth's orbit can exert huge influence on Earth's climate and are accountable for triggering the beginning and end of glaciation periods or ice ages (Buis 2020). Solar irradiance is the primary source of energy, and its variation directly influences the climate system. The total solar output at the top of the TOA is about 1360 $W\ m^{-2}$ (Kopp and Lean 2011). Being directly related to temperature, solar intensity changes Earth's temperature. Temperature rises as SI increases and vice versa. The estimated RF owing to variations in total SI over the industrial era is positive, causing rise in surface temperature. However, these changes in RF due to changes in solar irradiance are smaller in quantum. Volcanic eruptions, though considered as natural disasters, are natural driver of CC that can cause short-term changes in climate. During volcanic eruptions many solid and gaseous substances including $CO_2$, CO, $SO_2$, $H_2S$, water vapor, dust, ash, black carbon, aerosols, and other suspended particles are released into the atmosphere. In atmosphere, $SO_2$ oxidizes and forms sulfuric acid ($H_2SO_4$) which, after condensation, forms suspended particles. These dust, ash, aerosols, and other suspended particles block solar radiation from reaching Earth and enhance Earth's albedo by scattering incoming radiation back to space, causing a negative forcing that lowers global temperatures (Robock 2000), an effect known as the haze-effect cooling or global dimming/cooling. It usually persists for a few years. Volcanic eruptions also emit small quantities of $CO_2$ and water vapor. However, estimates suggest that annual emissions of $CO_2$ from volcanic eruptions are less than 1% of all anthropogenic $CO_2$ emissions (Gerlach 2011). Moreover, changes in RF due to volcanic eruptions are negligible compared with other climate drivers as the episodes of volcanic eruptions in past few centuries have been quite low and sporadic.

#### 2.4.1.2 Anthropogenic Drivers

Though the natural drivers contribute to the rise of concentration of atmospheric GHGs, they can't justify the current rapid warming of average EST (Buis 2020). The long-term climatic trend observed over the last century can only be attributed to the effects of anthropogenic activities. Human activities contribute a significant amount of GHGs in the atmosphere in the forms of $CO_2$, $N_2O$, $CH_4$, and fluorinated gases (F-gases). Human-led drivers of changes can be divided into "well-mixed

**Table 2.1** Relative contributions (%) of GHGs to total anthropogenic GHG emissions per year between 1970 and 2010 (modified from IPCC 2021, 2022)

| GHGs | 1970 | 1990 | 2000 | 2010 | 2019 |
|---|---|---|---|---|---|
| $CO_2$ (from industry and fossil fuel) | 55% | 59% | 61% | 65% | 64% |
| $CO_2$ (from LULUCF) | 17% | 13% | 12% | 10% | 11% |
| $CH_4$ | 19% | 21% | 20% | 18% | 18% |
| $N_2O$ | 7.9% | 5% | 5% | 5% | 4% |
| F-gases | 0.44% | 1% | 2% | 2% | 2% |
| Total emissions (Gt $CO_2$-eq year$^{-1}$) | 27 | 38 | 42 | 53 | 59 |

greenhouse gases" (WMGHGs), "short-lived climate forcers" (SLCFs including $CH_4$, some hydrofluorocarbons, ozone, and aerosols), contrails, and albedo modification due to land use. The GHGs are the dominant human-influenced drivers of CC. Human actions such as combustion of fossil fuel for transportation and energy, biomass burning, changes in land-use pattern, wastewater treatment, livestock rearing, etc. lead to rapid emissions of these GHGs that enter the atmosphere.

It is unequivocal that anthropogenic activities led to the rapid increase in WMGHGs ($CO_2$, $CH_4$, and $N_2O$) in atmosphere since the pre-industrial period and even with a greater rate since 2000. Among the WMGHGs, $CO_2$ remains the major GHG with largest share of total annual anthropogenic GHG emissions. Industrial processes, fossil fuel burning, and "Land Use, Land-Use Change and Forestry" (LULUCF) are the strongest drivers of human-led $CO_2$ emissions. Net $CO_2$ flux (including removals) in the atmosphere arises from LULUCF that includes degradation, deforestation, peat drainage, and regrowth after agricultural abandonment (Canadell et al. 2021; Friedlingstein et al. 2020). Human actions like manure management, biomass burning, and agriculture (dominated by enteric fermentation from livestock and paddy cultivation) drive $CH_4$ emissions. On the other hand, higher use of nitrogenous fertilizers and manure accounts for about 2/3rd of the $N_2O$ emissions, while biomass burning, industry/fossil fuels, and wastewater accomplishing for the rest (Canadell et al. 2021). These are the major driving forces that change the climate system (Table 2.1).

Over the industrial period (1750–2019), total cumulative human-led $CO_2$ emissions to the atmosphere were 685 ± 75 PgC (Table 2.2). About half of the emitted anthropogenic $CO_2$ have occurred in the last few decades. Of this, 65% (445 ± 20 PgC) of total emissions were attributed to emissions from fossil fuels and industry, and LULUCF accounted for the rest (240 ± 70 PgC). About 42% emissions have persisted in the atmosphere (285 ± 5 PgC) and around 33% (230 ± 60 PgC) have been pulled out from the atmosphere and reserved on land (vegetation and soils). The oceans have taken up about 25% (170 ± 20 PgC) of the cumulative $CO_2$ emissions, causing ocean acidification (Canadell et al. 2021). Globally, continued and rising fossil fuel burning and industrial actions led by economic and population growth have been the most important drivers of $CO_2$ emissions (IPCC 2022). However, GHG emissions are not uniform across the globe and differ regionally,

**Table 2.2** Global anthropogenic $CO_2$ budget

| Source/sink of $CO_2$ | Cumulative emissions (PgC) 1750–2019 | Cumulative emissions (PgC) 1850–2019 | Mean annual growth rate (PgC per year) 2000–2009 | Mean annual growth rate (PgC per year) 2010–2019 |
|---|---|---|---|---|
| **Emissions** | | | | |
| Fossil fuel burning and manufacturing of cement | 445 ± 20 | 445 ± 20 | 7.7 ± 0.4 | 9.4 ± 0.5 |
| Net change in land use | 240 ± 70 | 210 ± 60 | 1.4 ± 0.7 | 1.6 ± 0.7 |
| Total emissions | 685 ± 75 | 655 ± 65 | 9.1 ± 0.8 | 10.9 ± 0.9 |
| **Partition** | | | | |
| Atmospheric rise | 285 ± 5 | 265 ± 5 | 4.1 ± 0.02 | 5.1 ± 0.02 |
| Ocean sink | 170 ± 20 | 160 ± 20 | 2.1 ± 0.5 | 2.5 ± 0.6 |
| Terrestrial sink | 230 ± 60 | 210 ± 55 | 2.9 ± 0.8 | 3.4 ± 0.9 |

and based on socioeconomic situations, different regions contribute to the emitted GHGs more or less than the others (Table 2.3).

Since the WMGHGs have the heat trapping capacity, abundance of these gases in the atmosphere plays a significant role in determining Earth's radiative properties (Canadell et al. 2021), causing a net accumulation of energy by the climate system. The warming or cooling effects these drivers of CC are estimated in terms of RF and/or effective radiative forcing (ERF) (Myhre et al. 2013). Total anthropogenic RF for 2011 relative to 1750 was estimated to 2.29 (1.1 to 3.3) W $m^{-2}$ which is 43% higher than that for 2005, owing to continued growth in WMGHG-related forcings. The RF of WMGHG ($CO_2$, $CH_4$, $N_2O$, and halocarbons) is 3.0 W $m^{-2}$ (Fig. 2.4). Thus, total anthropogenic RF is mainly influenced by the combined effect of WMGHGs, particularly $CO_2$, $CH_4$, and $N_2O$. This rise in RF of WMGHGs could be largely attributed to rapid increase in $CO_2$-related RF. Industrial era RF for $CO_2$ in 2011 relative to 1750 alone is 1.68 W $m^{-2}$, making it the component with largest global mean RF, followed by $CH_4$ (0.97 W $m^{-2}$), halocarbons (0.18 W $m^{-2}$), and $NO_2$ (0.17 W $m^{-2}$) (Fig. 2.4). Ozone contributes substantially to total RF. The total estimated RF owing to changes in ozone is 0.35 W $m^{-2}$ (0.40 W $m^{-2}$ for tropospheric ozone changes and − 0.05 W $m^{-2}$ for stratospheric ozone changes). Since the 1960s, $CO_2$ is the single largest contributor to the increased anthropogenic RF in each decade. Between 1960 and 2019, the relative contributions of $CO_2$, $CH_4$, $N_2O$, and halogenated species to the total ERF was 63%, 11%, 6%, and 17% (Canadell et al. 2021). The net anthropogenic forcings by WMGHGs other than $CO_2$ are quite small. Black carbon, a short-lived climate pollutant and a potent global warming agent, is the second most important contributor to global warming following $CO_2$. However, it does not have long persistence in the atmosphere like $CO_2$ and $N_2O$. Few anthropogenic drivers such as aerosols (except for black carbon aerosol on snow and ice which has positive forcing) and surface albedo (due to land-use change) contribute to reductions in RF, but they are not enough to offset the

**Table 2.3** Differential $CO_2$ emissions across regions (IPCC 2022)

| | Africa | Australia, Japan, New Zealand | E. Europe, West-Central Asia | E. Asia | Europe | Caribbean and Latin America | Middle East | N. America | S. Asia | SE Asia and Pacific |
|---|---|---|---|---|---|---|---|---|---|---|
| Population (million, 2019) | 1292 | 157 | 291 | 1471 | 620 | 646 | 252 | 366 | 1836 | 674 |
| GDP per capita (USD1000ppp2017 per person) | 5.0 | 43 | 20 | 17 | 43 | 15 | 20 | 61 | 6.2 | 12 |
| % GHG contributions | 9 | 3 | 6 | 27 | 8 | 10 | 5 | 12 | 8 | 9 |
| GHG per person ($tCO_2$-eq per capita) | 3.9 | 13 | 13 | 11 | 7.8 | 9.2 | 13 | 19 | 2.6 | 7.9 |

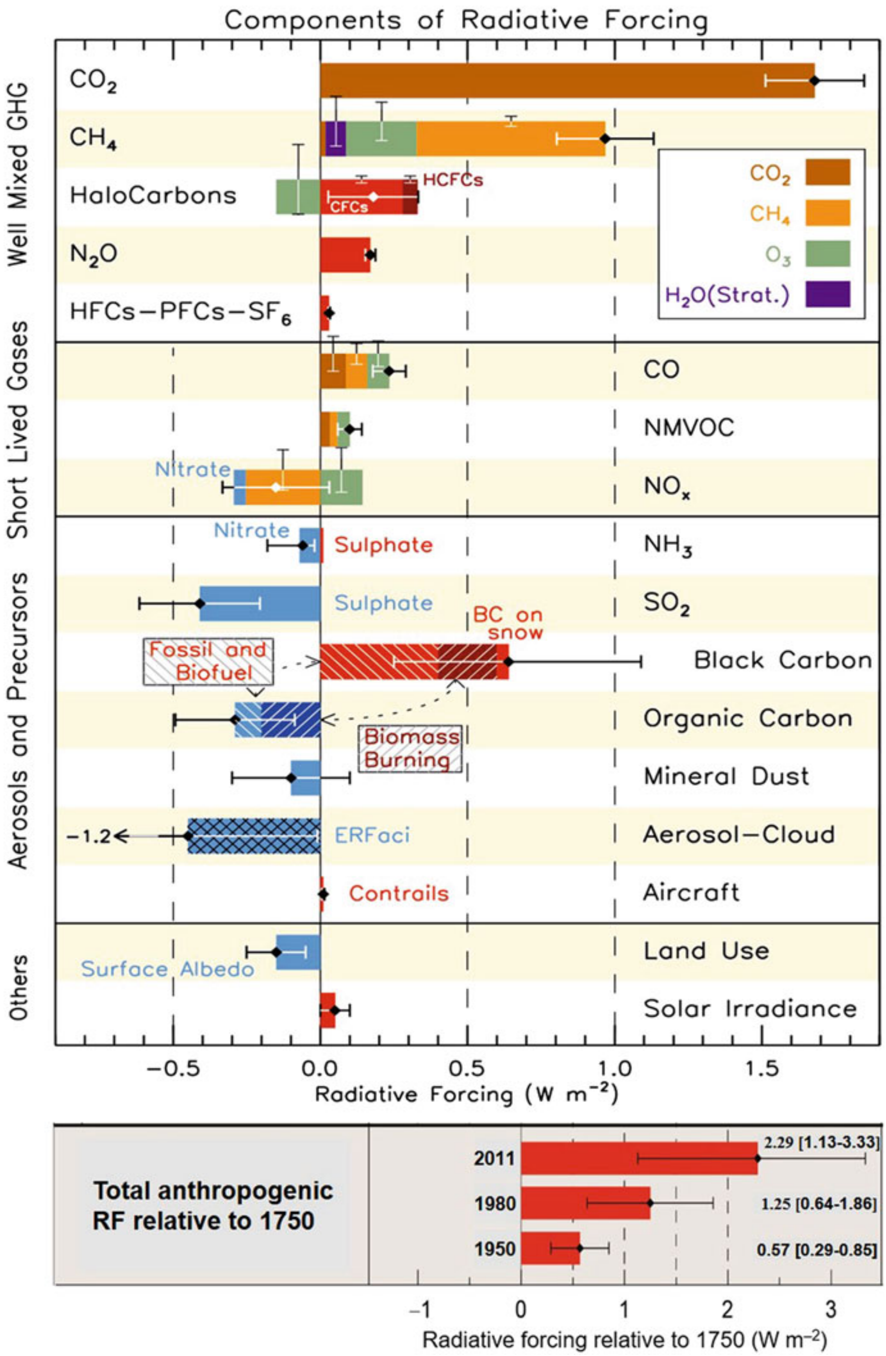

**Fig. 2.4** Radiative forcing (RF) estimates in 2011 relative to 1750 for the main drivers of CC (IPCC 2013)

increased anthropogenic forcing of WMGHGs, particularly $CO_2$ (Fig. 2.4). Thus, human-induced GHG emissions led to the current surface warming.

### 2.4.2 Impacts of CC

CC is likely to cause a cascade of side effects on the natural and human systems including biodiversity, food systems, water resources, coastal ecosystems, cities and infrastructure, and human health across the globe. However, the effects of CC are already more or less visible. CC is a global phenomenon, and its effects are to be observed globally, yet some regions may become more vulnerable to these impacts than others. Although majority of these impacts are likely to be negative, some benefits may occur in some regions. The observed and predicted impacts of CC are summarized below.

| | |
|---|---|
| Agriculture and food security | Higher atmospheric $CO_2$ levels will increase rate of photosynthesis and plant growth, known as $CO_2$ fertilizing effect. Crops in warmer regions are expected to face the net negative impacts of CC as occurrences of droughts and heat-stress are likely to rise<br>Productivity of winter crops of tropical regions is likely to decrease as a result of shorter grain filling periods owing to shrinking winter period<br>Yields of $C_4$ plants (tropical grasses, maize, sorghum, sugarcane, etc.) are not expected to increase (Leakey 2006). Growth and yields of $C_3$ crops (rice, soybean, wheat, etc.) may increase due to rising $CO_2$ concentrations. However, higher $CO_2$ levels are associated with elevated ambient temperature which is likely to have harmful impact on crop growth as higher ambient temperature increases photorespiration in $C_3$ plants. So, the combined effects of elevated $CO_2$ and temperature will exert a mixed outcome; more specifically a net negative effect on agricultural productivity, especially in the warmer regions (Liu et al. 2018)<br>Productivity of crops, livestock, and fisheries may be declining due to EWEs, changing temperature and rainfall patterns, giving rise to hunger and malnutrition<br>Vector-borne diseases and other illnesses of livestock are likely to increase |
| Water resources | With rising MSLs, sea water will intrude low-lying coastal areas, causing scarcity of freshwater<br>Glacier-fed water supplies will reduce, rivers will dry up, and water will become scarcer in many regions with higher risks of desertification<br>Water shortages will hit the already water-stressed regions severely, leading to agricultural droughts and ecological droughts |
| Biodiversity | Many climate-sensitive terrestrial and aquatic organisms are estimated to disappear at a rapid rate with rising temperature<br>Abundance of noxious invasive species will increase. This may lead to natural habitat destruction and lower food availability |
| Sea level rise and marine life | Average sea levels have risen by 19 cm since the commencement of twentieth century resulting into frequent flooding in many coastal areas (IPCC 2013)<br>Coral bleaching and lower abundance of planktons due to ocean |

(continued)

| | |
|---|---|
| | acidification and warmer water will lead to natural habitat destruction and lower food availability for thousands of aquatic species |
| Extreme weather events | With rising GHGs in atmosphere, global surface temperature is also rising. Every decade happens to be warmer than the previous leading to occurrence of droughts on a regular basis.<br>Storms such as cyclones, hurricanes, and typhoons thrive as ocean temperature increases. Tropical storms have become more destructive with higher frequency and intensity in many regions which leads to greater risks of flooding. |
| Human and society | Human health hazards will be increased with more incidence of heat-related deaths in many regions of the world as heatwaves and droughts have become more common<br>Heat stress will lead to more respiratory and cardiovascular diseases with higher rates of mortality; cold-related deaths are likely to decrease<br>CC will affect environmental and social determinants of health like water and air quality, food, and secure shelter. Climate factors lead to death of around 13 million people annually (UN 2022). CC is likely to cause around 250,000 deaths per annum between 2030 and 2050 due to malnutrition and food-borne diseases, malaria, diarrhea, heat stress, extreme weather events, waterborne diseases, respiratory illness, noncommunicable diseases, etc. (WHO 2021)<br>Inundation of coastal regions could result in massive human migration (climate migrants) (Pelling and Blackburn 2013). This could lead to conflicts and global humanitarian crises. Between 2010 and 2019, on average 23.1 million people were displaced per year due to weather-related events (UN 2022)<br>CC will hit the economies of countries. One estimate suggested roughly 23% reductions in mean global incomes by 2100 with unwarranted global warming (Burke et al. 2015). Countries that depend on agriculture a lot will be at the risk of economic and social crisis<br>Developing countries and poor and vulnerable communities with fewer resources to adapt will be impacted the most, particularly in regions of Africa and Asia |

## 2.5 Predict Future CC

A climate prediction is a probabilistic declaration regarding the future geographical (global, regional, or local) and temporal (months to years) climate conditions. It is based on current conditions and scientific knowledge of the physical and dynamical processes that govern changes in the future. National and international investments in climate observations, research, and modelling during the last few decades have significantly improved scientific knowledge of climate variability and change while also advancing experimental and real-world climate prediction. These initiatives offer a solid scientific basis for developing climate prediction products, i.e., goods based on projections for the months and years to come. In order to manage development opportunities and hazards, as well as for adaptation and mitigation, timely, actionable, and trustworthy climate prediction plays a critical role in decision-making for individual users, users in a number of industries, and national development planning.

Climate models (CMs) are mathematical representations of key climate-related phenomena. The results of a hierarchy of climate models – from basic idealized models through models of intermediate complexity to thorough “general circulation models” (GCMs), including “Earth system models” (ESMs) that mimic the carbon cycle – are taken into consideration. The precipitation, atmospheric temperature, winds, ocean currents, clouds, and the quantity of sea ice are only a few of the many climate factors that the GCMs simulate. The models are rigorously examined against historical data. It is essential to be able to forecast these developments so that we can be ready for them when they occur and have the drive to cut emissions. The CMs use data from GHG and air pollutant emission scenarios and land-use trends to provide projections of CC. A variety of methods, from straightforward idealized experiments to “integrated assessment models” (IAMs), are used to create scenarios. The following two theories were established by IPCC to forecast future climatic conditions:

- “Representative Concentration Pathways” (RCPs)
- “Shared Socioeconomic Pathways” (SSPs).

### 2.5.1 Representative Concentration Pathways (RCPs)

An RCP is a pathway for GHG concentrations that the IPCC has chosen. In the 2014 IPCC AR5, four pathways were employed for climate research and modelling. Various climate scenarios are depicted in the pathways, all of which are thought to be feasible given the level of GHG emissions in the coming years. The different RCPs, i.e., RCP2.6 (2.6 W $m^{-2}$), RCP4.5 (4.5 W $m^{-2}$), RCP6.0 (6.0 W $m^{-2}$), and RCP8.5 (8.5 W $m^{-2}$), are named after a potential range of radiative forcing levels in 2100. The impacts of RCPs on the climate system have been projected using IAMs as input to a variety of CM simulations. Assessments of consequences and adaptation strategies are then based on these climate estimates. The RCPs outline four distinct trajectories for land use, air pollutant emissions, and GHG emissions in the twenty-first century. There are RCP8.5 as a “very high GHG emission scenario,” a “strict mitigation scenario” (RCP2.6), and two “intermediate scenarios” (RCP6.0 and RCP4.5) and (Fig. 2.5). Scenarios that don’t make any additional effort to limit emissions (also known as “baseline scenarios”) result in trajectories between RCP6.0 and RCP8.5. RCPs are described in terms of inputs; a significant difference between the 2007 and 2014 IPCC reports is that the RCPs neglect the carbon cycle by focusing on concentrations rather than inputs of GHGs. The “Special Report on Emissions Scenarios” (SRES) (based on comparable socioeconomic models) (published in 2000) estimates were replaced by the RCP scenarios (Ward et al. 2012). RCP8.5, RCP6.0, and RCP4.5 are compared to the SRES A2/A1FI, B2, and B1, respectively, in terms of overall forcing. There isn’t a comparable situation in SRES for RCP2.6. As a result, the inclusion of the wider range of evaluated

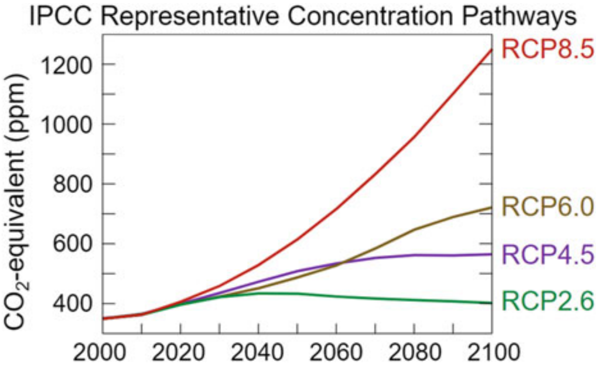

**Fig. 2.5** Atmospheric $CO_2$-equivalent concentrations of all forcing agents according to the four RCPs (IPCC 2014)

emissions accounts for a major portion of the changes in the magnitude of AR4 and AR5 climatic estimates.

#### 2.5.1.1 RCP2.6

RCP2.6 suggests that $CO_2$ emission must start to decline by 2020 and go to zero by 2100. Additionally, it calls for a decrease in $SO_2$ emissions to 10% of 1980–1990 levels and a reduction in methane emissions ($CH_4$) to roughly 50% of 2020 levels. RCP2.6, like all the other RCPs, calls for negative $CO_2$ emissions ($CO_2$ absorption by trees). These negative emissions would amount to an annual average of 2 gigatons of $CO_2$ (Gt $CO_2$/yr). By 2100, the global temperature rise is anticipated to be limited by RCP2.6 to 2 °C (IPCC 2014).

#### 2.5.1.2 RCP4.5

IPCC refers to RCP4.5 as intermediary scenario. In RCP4.5, emissions will be highest about 2040 and then start to fall. The resource experts claim that IPCC emission scenarios are prejudiced toward inflated availability of fossil fuel reserves. Considering the exhaustible nature of nonrenewable fuels, RCP4.5 is the most likely "baseline scenario" (no climate policy). $CO_2$ emissions must begin to decline by around 2045 in order to be around half of 2050 levels by 2100. Additionally, it mandates that $SO_2$ emissions decrease to roughly 20% of those of 1980–1990 by 2050 and that $CH_4$ emissions decrease somewhat to about 75% of its levels of 2040. Additionally, RCP4.5 calls for negative $CO_2$ emissions, or 2 Gt $CO_2$/yr., through things like trees absorbing $CO_2$. By 2100, it is more likely than not to world's temperature rise by 2–3 °C under RCP4.5, with a 35% higher MSL rise than under RCP2.6 (IPCC 2014). Numerous species of plants and animals won't be able to withstand the consequences of RCP4.5 and 6.0 and 8.5.

#### 2.5.1.3 RCP6.0

Emissions in RCP6.0 reach their maximum level about 2080 before declining. It uses a high rate of GHG emissions and is a "stabilization scenario" where total RF is stabilized after 2100 by the deployment of a variety of technologies and tactics for diminishing GHG emissions. The radiative forcing attained by 2100 is 6.0 W $m^{-2}$.

RCP6.0 scenario predicts that global warming will continue through 2100, and $CO_2$ levels will increase to 670 ppm by that time, causing a 3–4 °C increase in average global temperature (IPCC 2014).

#### 2.5.1.4 RCP8.5

Emissions in RCP8.5 increase throughout the twenty-first century (IPCC 2014). This has been regarded to be extremely implausible since AR5 but still possible as feedbacks are not well understood. The worst-case CC scenario, RCP8.5, was predicated on what turned out to be an overestimation of anticipated coal production (Schwalm et al. 2020).

### 2.5.2 RCP-Based Projected Changes in the Climate System

The "Coupled Model Intercomparison Project Phase 5" (CMIP5) of the "World Climate Research Programme" employed the RCPs in climate model simulations. Because of increased $CO_2$ emissions into the atmosphere during the twenty-first century, atmospheric $CO_2$ concentrations in all RCPs are greater in 2100 than they are today. All the projections under RCPs depicts the scenario for the twenty-first century end (2081–2100) as compared to 1986–2005, otherwise stated.

#### 2.5.2.1 Future Change in Atmospheric Temperature

In comparison to 1986–2005, change in average global surface temperature from 2016–2035 will probably be between 0.3 and 0.7 °C. The conclusion is based on a number of evidence lines and assumed the absence of significant volcanic outbreaks and secular fluctuations in solar irradiation. In comparison to natural internal variability, it is projected that near-term rises in seasonal and annual average temperatures will be higher in tropical and subtropical regions than midlatitudes. The concentration-driven CMIP5 model simulations predict an increase in global mean surface temperatures (2081–2100) compared to 1986–2005 that falls between the following ranges: 2.6–4.8 °C (RCP8.5), 1.4–3.1 °C (RCP6.0), 1.1–2.6 °C (RCP4.5), and 0.3–1.7 °C (RCP2.6) (Fig. 2.6 and 2.7). The average warming of land will be greater than that of over sea, and the warming rate of Arctic will be higher than global average. RCP8.5, RCP6.0, and RCP4.5 predict that by the twenty-first century end, the average global ST will have increased by >1.5 °C as compared to the average of 1850–1900. Warming is unlikely to exceed 2 °C for RCP2.6, more likely than not to exceed 2 °C for RCP4.5, but expected to surpass 2 °C for RCP6.0 and RCP8.5. For RCP6.0, RCP4.5, and RCP2.6, warming is highly unlikely to surpass 4 °C, and for RCP8.5, it is essentially certain not to exceed 4 °C. On a daily and seasonal scale, it is almost certain that with the rise in global mean temperatures, there will be higher hot and fewer cold temperature extremes throughout the majority of land areas. There is a good chance of more frequent and last longer heat waves. Winter weather extremes will occasionally happen.

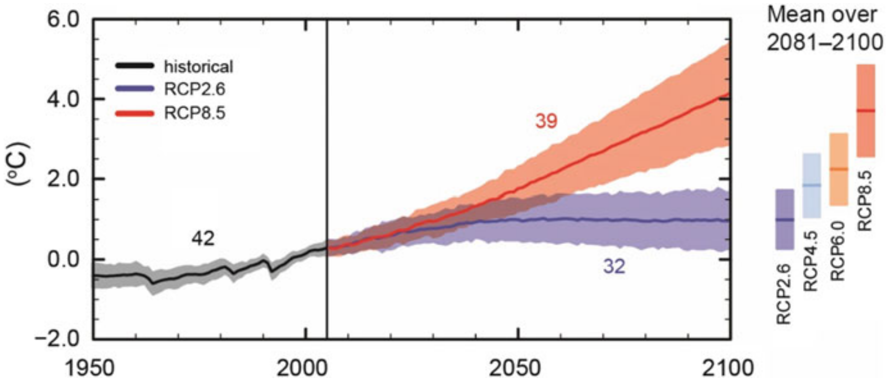

**Fig. 2.6** Changes in global mean surface temperature (CMIP5 simulated) from 1950 to 2100 as compared to 1986–2005

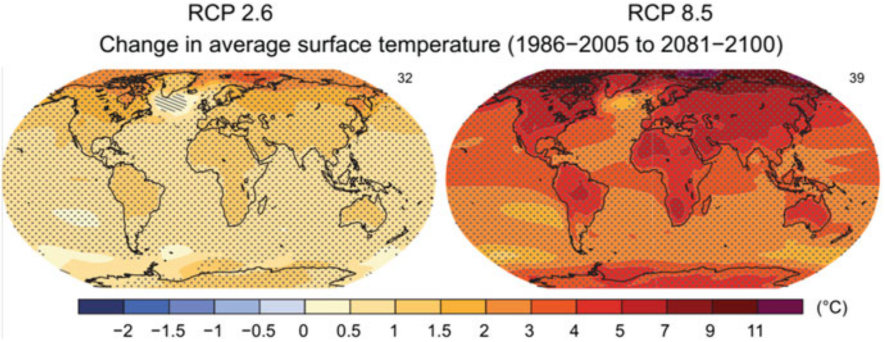

**Fig. 2.7** Maps of annual mean surface temperature change (CMIP5 simulated) in 2081–2100 relative to 1986–2005

### 2.5.2.2 Future Change in Carbon Cycles

Under all four RCPs, oceanic uptake of anthropogenic $CO_2$ will persist through 2100, with more uptakes for higher concentration trajectories. Less is known about how the land will absorb carbon in the future. Most models predict that land will continue to absorb carbon under all RCPs, while other models even predict that land will lose carbon due to the consequences of both land-use change and CC put together. The majority of CMIP5 and ESM simulations were run with the $CO_2$ levels of 936 (RCP8.5), 670 (RCP6.0), 538 (RCP4.5), and 421(RCP2.6) ppm reaching by the year 2100. The total $CO_2$-equivalent values are 1313, 800, 630, and 475 ppm for RCP8.5, 6.0, 4.5, and 2.6, respectively, when the specified quantities of $CH_4$ and $N_2O$ are also taken into account. There will be a positive relationship between temperature and carbon cycle in the twenty-first century which is based on ESMs, that is, CC will partially counterbalance the rise in ocean and land carbon reserves brought on by atmospheric $CO_2$ rise. Consequently, most of the anthropogenic $CO_2$ that has been released will stay in the atmosphere. According to

**Table 2.4** Cumulative $CO_2$ emissions (CMIP5 simulated) during the period of 2012–2100

| | Cumulative $CO_2$ emission (2012–2100) | | | |
|---|---|---|---|---|
| | $GtCO_2$ | | GtC | |
| Scenario | Range | Mean | Range | Mean |
| RCP8.5 | 5185–7005 | 6180 | 1415–1910 | 1685 |
| RCP6.0 | 3080–4585 | 3885 | 840–1250 | 1060 |
| RCP4.5 | 2180–3690 | 2860 | 595–1005 | 780 |
| RCP2.6 | 510–1505 | 990 | 140–410 | 270 |

**Fig. 2.8** Various pathways of SSPs for mitigation/adaptation with respect to challenges

15 Earth system models, the total $CO_2$ emissions for the period from 2012 to 2100 that are consistent with the RCP atmospheric $CO_2$ concentrations range from 1415 to 1910 Gt C for RCP8.5, 840 to 1250 Gt C for RCP6.0, 595 to 1005 Gt C for RCP4.5, and 140 to 410 Gt C for RCP2.6 (Table 2.4). Annual $CO_2$ emissions under RCP2.6 will be 14 to 96% less by 2050 than they were in 1990. According to RCP8.5, the thawing permafrost carbon reserves is expected to release 50–250 GtC in the form of $CO_2$ or $CH_4$ to the atmosphere over the twenty-first century.

## 2.5.3 Shared Socioeconomic Pathways (SSPs)

Projections of anticipated worldwide socioeconomic trends through the year 2100 are known as socioeconomic pathways (SSPs). These are used to develop GHG emission scenarios under different climate policies (Fig. 2.8). They contributed to the sixth Assessment Report on CC (AR6) of IPCC, which was published on August 9, 2021. The SSPs' narratives give an alternative socioeconomic development's description. These plot lines act as a qualitative description of the connections between different narrative elements. For the quantitative components, they supply information on the scenarios' effects on the national population, urbanization, and GDP (per capita). Several IAMs can be used to measure SSPs and examine potential future socioeconomic and climatic trajectories. The many SSP types are as follows (Hausfather 2018):

#### 2.5.3.1 SSP1: "Sustainability"

Slowly but gradually, the world is heading toward a more sustainable path, giving more importance on inclusive development. There is a gradual improvement in global commons' management, demographic change is accelerated by spending on healthcare and education, and the importance swings from economic growth to human well-being. The rising commitment of achieving development goals forces to reduce inequality internationally and among individual nations (Riahi et al. 2017; Van Vuuren et al. 2017).

#### 2.5.3.2 SSP2: "Middle of the Road"

The globe travels on a course where social, technical, and economic tendencies don't diverge significantly from past patterns. Uneven progress is being made in terms of development and income growth, though some nations performing better than anticipated while others fall short. Goals for sustainable development are being pursued by national and international agencies, but they are moving slowly in that direction. Although there have been some advances, overall resource and energy-use intensity is declining while environmental system is degrading. The rate of population growth in the world decreases to a moderate rate in the second half of the century. Lowering vulnerability to environmental and societal changes remains difficult, and economic inequality either persists or slowly gets better (Riahi et al. 2017; Fricko et al. 2017).

#### 2.5.3.3 SSP3: "Regional Rivalry"

A return of nationalism worries around competition and security, and provincial struggles are forcing nations to emphasis more on domestic and regional issues. Continuous evolvement of policies become more concerned with both domestic and international security challenges. Countries prioritize regional growth over achieving the objectives of ensuring the energy and food security of those regions. Education and technological innovation are receiving less funding. Spending is materialistic, economic growth is sluggish, and inequalities continue or deteriorate over time. In developing countries, population growth is high, while it is low in industrialized countries. Little international attention is given to environmental issues, which in certain places results in serious environmental degradation (Riahi et al. 2017; Fujimori et al. 2017).

#### 2.5.3.4 SSP4: "Inequality"

High differences in investments of human capital, together with expanding gaps in economic opportunities and political influence, contribute to rising inequality and stratification both within and within nations. The divide between a globally interconnected civilization that supports capital- and knowledge-intensive sectors in global economy and a dispersed group of lesser-income, less-educated cultures that participate in a labor-intensive, low-tech economy expands with time. Conflict and instability increase when societal cohesion decreases. Rapid technical advancement is observed in the high-tech industry and sectors (Riahi et al. 2017; Calvin et al. 2017).

#### 2.5.3.5 SSP5: "Fossil-Fueled Development"

This society increasingly relies on competitive markets, participatory communities, and innovations to enable rapid technological advances and the growth of human capital – two crucial components of sustainable development. The global economy is becoming more linked. To increase human and social capital, there are also significant funds in institutions, education, and health. The global embrace of resource- and energy-concentrated lifestyles, together with the drive for economic and social progress, goes hand in hand with the extraction of copious fossil fuel reserves. All these variables contribute to the rapid rise of the global economy. Air pollution and other local environmental issues are successfully controlled (Riahi et al. 2017; Kriegler et al. 2017).

### 2.5.4 SSP-Based Future Climate Projections

Five explanatory scenarios (Table 2.5) that represent the spectrum of potential future developments of human-led causes of CC are used in AR6 to analyze the climate response. The SSPs on which these scenarios are based (SSP1–SSP5) are coupled with the anticipated range of radiative forcing in 2100 (1.9–8.5 W $m^{-2}$) to form the names of these scenarios (Table 2.5). The likelihoods of the scenarios were not

**Table 2.5** Changes in global mean surface temperature based on SSP scenarios (IPCC 2021)

| Scenarios | SSP | $CO_2$ emission scenario | Temp. change (°C) (2021–2040) | Temp. change (°C) (2041–2060) | Temp. change (°C) (2081–2100) |
|---|---|---|---|---|---|
| GHG emissions: Very low | SSP1–1.9 | Net zero around 2050 | 1.5 | 1.6 | 1.4 |
| GHG emissions: Low | SSP1–2.6 | Net zero around 2075 | 1.5 | 1.7 | 1.8 |
| GHG emissions: Intermediate | SSP2–4.5 | Remains present levels till 2050 followed by falling but never reach by 2100 to net zero | 1.5 | 2.0 | 2.7 |
| GHG emissions: High | SSP3–7.0 | Double by 2100 | 1.5 | 2.1 | 3.6 |
| GHG emissions: Very high | SSP5–8.5 | Triple by 2075 | 1.6 | 2.4 | 4.4 |

estimated in the IPCC Sixth report (IPCC 2021), but a 2020 commentary characterized SSP2–4.5, SSP3–7.0, and SSP5–8.5, as likely, unlikely, and highly unlikely, respectively. But according to a paper referencing the discussion above, RCP8.5 best approximates the total emissions from 2005 to 2020. The future climate prediction based on SSP concept began in 2015. The scenarios with very high and high GHG emissions (SSP5–8.5 and SSP3–7.0) show that $CO_2$ emissions were almost twofold from present levels by 2050 and 2100, respectively. SSP2–4.5 is considered as a "scenario with intermediate GHG emissions" in which $CO_2$ emissions remain constant till mid-twenty-first century. As seen in SSP1–2.6 and SSP1–1.9 ("scenarios with low and very low GHG emissions"), $CO_2$ emissions reach net zero by 2075 and 2050, respectively (Fig. 2.9). Depending on socioeconomic assumptions, degrees of CC mitigation, and air pollution controls, emissions vary between scenarios. Alternative assumptions might produce comparable emissions and climate responses.

The SSPs' conceptual framework based five scenarios were also evaluated for their expected temperature results in the IPCC's AR6. The probable temperature rise, according to co-authors of AR6, will be 1.5–5 °C in mid of the scenario spectrum, and it will be 3 °C in 2100. 1.5 °C will probably be attained by 2040 (IPCC 2021). Comparative to earlier IPCC reports, the hazards from compound impacts are regarded as greater. Temperature-related increases in extreme weather are anticipated, and compound impacts (i.e., drought and heat together) could have a greater social impact.

## 2.6 Strategies for Combating CC Effects

The effects of CC are very much prominent in different environmental compartments. Therefore, several strategies singly and in combination should be adopted to reduce these detrimental impacts. The needful strategies in this regard have been depicted in the following subsections.

### 2.6.1 Afforestation and Reforestation

The term "afforestation" is actually the expansion of forests or the planting of trees in areas that were either previously devoid of tree cover or not recognized as forests. To establish a forest, one must plant trees or scatter seeds across a barren landscape. Reforestation is considered as the growing of trees in a forest area where the number of trees is gradually declining. It is the process of preparing a new forest or adding more trees to an already existing forest area. Both of these methods, i.e., afforestation and reforestation are conscious attempts to encourage the growth of trees as a potent strategy to eliminate the evil effects of CC (Doelman et al. 2020; Lin et al. 2020).

There are several different kinds of afforestation techniques, such as sowing thick plots of numerous plant species of indigenous origin and establishing a single plant species, whereas restoration of native forests, wood plantations, or agroforests/

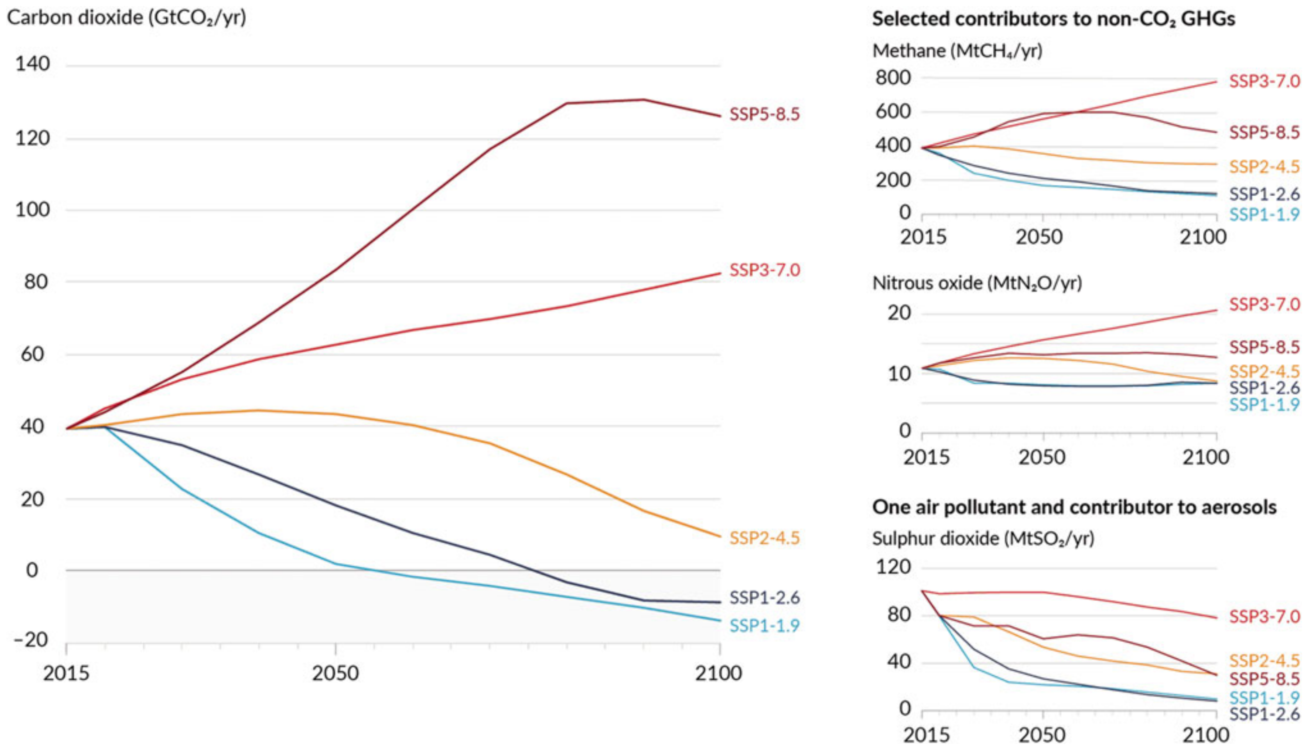

**Fig. 2.9** Prediction of SSP-based future annual emissions of $CO_2$ and of a subset of key non-$CO_2$ drivers (right) (IPCC 2021)

multipurpose trees are all examples of reforestation efforts. Plantations that involve planting trees for timber, fiber, and carbon offsets are becoming more commonplace worldwide. There are three main ways that efficient forest management practices can contribute to the decrease of atmospheric $CO_2$ (Akanwa et al. 2019):

(i) **Carbon sequestration:** It is the process that makes use of different techniques such as reforestation, afforestation, restoration of damaged lands, agri-/horti-/silvicultural techniques to speed up plant growth rates, and also the application of the agroforestry techniques.
(ii) **Carbon conservation:** This strategy is implemented by using several techniques such as conserving the soil carbon (C) and biomass in the forest areas and improved harvesting procedures, such as greater wood processing efficiency, decreased impact logging, protection of the forest plantations from fires, and more efficient use of burning in both agricultural and forest systems. C conservation has been scientifically proven to have the highest chances for quick CC mitigation.
(iii) **Carbon substitution:** It involves the increased use of biofuels. To accomplish this, the enhanced use of different wastes as a feedstock for developing biofuels, development of different bioenergy plantations, and the greater transformation of the forest biomass into durable wood products is required.

### 2.6.2 Environmental Greening

The protection of resources, the improvement of socioeconomic well-being, and the aesthetics and design of the landscape all benefit from greening the rural and urban environment (Akanwa et al. 2020; Sharifi 2021). In rural greening, agricultural practices, the use of forest products, and the exploitation of natural resources all directly depend on the economic environment of the rural people. According to the ILO (2014), the economies of the rural people should be strengthened through use of clean energy, adoption of different sustainable agricultural practices, restoration of degraded ecosystems, environmental protection, income diversification, promotion of sustainable tourism, and promotion of social dialogue to make the transition to sustainable economies successful, inclusive, and fruitful.

The urban-rural interface is the meeting area of a town or city with a rural area. The competition for space and effectiveness of green infrastructure are two major problems in this peri-urban transition zone. The ecosystem services are provided by green infrastructure in this area, including reducing the "heat island" effect from urban areas, constructing ventilation channels, and promoting the movement of cleaner, fresher air from the countryside into the city.

Urban greening as a concept is quickly gaining appeal (Li and Wang 2021). It is an integrated strategy of planting trees and managing vegetation in an urban area to provide people with several environmental and social benefits (Miller et al. 2015). Various programs such as planting residential and street trees; creating public parks, home or kitchen gardens, greenbelts, and greenways, developing watershed management programs; etc. can contribute to achieving a successful urban greening initiative.

### 2.6.3 Agroforestry

Agroforestry is a practice that can reduce the greenhouse effect and combat CC by sequestering carbon (van Noordwijk et al. 2021). Being an eco-friendly method of managing land that integrates both forestry and agricultural techniques, agroforestry lessens atmospheric carbon (Singh and Jhariya 2016). On the same plot of land, trees are purposefully incorporated alongside animals, crops, and both simultaneously and sequentially. Agroforestry systems are sustainable, eco-friendly techniques that reduce atmospheric $CO_2$ emissions and CC.

### 2.6.4 Climate-Smart Agricultural Practices

Cover crops, residue mulching, no-till farming, and crop rotation are methods that significantly enhance the storage of soil C; all of these methods are used more frequently in organic farming (Zerssa et al. 2021). These methods along with the conversion of arable land to grassland, use of drought-tolerant crop varieties, straw combination, reduced tillage, alley cropping, etc. are considered as climate-resilient agricultural techniques to conserve soil organic carbon. Reducing groundwater abstraction is also important in this regard. Moreover, stopping crop residue burning and adopting their alternate usage and/or disposal strategy may reduce environmental pollution as well as adverse CC effects (Barman and Mukhopadhyay 2020).

### 2.6.5 Transport

Javadinejad et al. (2019) highlighted the use of modern energy-efficient machines to reduce the use of petroleum fuels and also the emissions of $CO_2$. Using rail transportation, especially electric trains, can significantly reduce the air pollution. The use of biofuel in transport vehicles is important in this regard to alleviate the adverse effects of CC (Prasad et al. 2020).

### 2.6.6 Societal Controls

Making tradeable, individual carbon credits available is another strategy that can be taken into consideration (Javadinejad et al. 2019). People will be motivated and inspired by the concept to reduce their carbon footprint through their daily behaviors.

### 2.6.7 Policies and Regulations

Standards for air quality have been employed in developed nations to shield the populace from exposure to various air contaminants (Dhakal et al. 2016). Enforcement of emission controls must occur when the standards are breached. However, developing nations face numerous difficulties in implementing policies due to various issues, such as lack of environmental awareness, poverty and hunger, ethnic unrest, religious conflicts, unstable and subpar leadership, insecurity, and improper management of resources and priorities. Despite the existence of a regulatory framework, these difficulties have persisted to undermine the enforcement of policy in developing countries. To reduce the deadly effects of CC, it is also important to improve the current legislative measures. Moreover, new legislative measures and regulatory frameworks should be developed and adopted to attain the environmental sustainability.

## 2.7 Conclusion

Concerns about the globe warming over the next century are being raised as a result of human activities that are causing $CO_2$ and other GHGs to accumulate in higher concentrations. Recent rises in the global average temperature over the past 10 years already seem to be outside the typical range of temperature variations during the previous 1000 years. Increasing atmospheric concentrations of GHGs are highly implicated in this temperature rise, as per various independent analyses, which supports the concerns of far more significant climatic changes in foreseeable future. If current trends of GHG emissions continue till the end of twenty-first century without adopting strong mitigation policies, Earth's surface temperature could increase by 3.6 °C to 4.4 °C relative to 1990, depending on the future population and economic growth. This will have serious effects on economic growth, environment and ecosystems, food security, water resources, and human health. However, future prediction of global CC is quite uncertain and requires more rigorous studies. But it is unequivocal that with unwarranted rate of emissions without policy actions, future global warming could reach a point beyond any possible recovery. To combat changing climatic conditions and to reduce GHG emissions, certain adaptation and mitigation strategies will be necessary. However, it takes government willingness and consensus among common people for an appropriate policy to become effective.

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# Vulnerability of Dryland Agriculture over Non-dryland Agriculture toward the Changing Climate

## 3

Shubham Singh and Shidayaichenbi Devi

## Abstract

Farming in dry areas is under threat because of climate change and not utilizing the land in a sustainable way. Around 40% of the earth's surface is made up of drylands including areas with very little water. These drylands are home to approximately 2.5 billion people. It is important for the farmers of the dryland areas to understand how climate change can affect them and what are the promising ways to face it. Moreover, the utilization of this area by growing crops is also necessary for feeding the ever-increasing population. However, the sustainability of livelihoods in drylands agriculture systems is threatened by a complex range of social, economic, political, and environmental changes. These changes present significant challenges to researchers, policymakers, and rural land users. However, these areas are highly sensitive to climate variability and change. The changing climate poses an imminent challenge to dryland farmers who practice a wide range of techniques from traditional methods to advanced irrigation systems for crop production. Different process-based models can also be helpful in designing the management options for dryland cropping systems that are more resilient to climate change. These models have been used in different regions around the world to quantify the impacts of climate change at the field, regional, and national scales. Therefore, future policies for sustainable agricultural production systems should take this into account. And technology-based regional collaborative interventions among universities, growers, companies, and others are needed to support agriculture in the face of climate change. In this article, we explore the vulnerability of dryland agriculture toward

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the changing climate as well as its potential for adaptation through different resilience measures. Therefore, the recommendations for better productivity in these areas require water and nutrient management, ideotype designing, modification in tillage practices, application of cover crops, insects, and disease management.

**Keywords**

Climate change · Dryland agriculture · Crop models · Climate model

## 3.1 Introduction

The surrounding of the earth's surface, i.e., the atmosphere, is increasing in its temperature since industrialization. It releases various forms of solar radiation-trapping and ozone-depleting compounds such as carbon dioxide ($CO_2$), chlorofluorocarbons (CFC), methane ($CH_4$), nitrous oxide ($N_2O$), etc. inducing climate change. As the movement of the atmospheric air from one region to another, climate change is a global issue other than where industries exist. It is not only due to industrialization but also due to mismanagement of lands, deforestation, faulty practices of agriculture, etc. Climate change affects dryland regions more as compared with non-dryland regions. The existence of dryland regions is in elevated temperature regions, and climate change further increases the temperature of these regions (Ahmed et al. 2022). With the elevation of temperature, the mineralization of organic materials is enhanced thereby the wide spreading of the dryland regions and degrading the environment. This directly impacts the social, economic, political, and environments of livelihoods. However, the non-dryland regions are less vulnerable to climate change as the mineralized organic materials can be substituted from the vegetation as the source. The coverage of dryland regions is almost half of the earth's surface. So the spreading of dryland regions due to climate change threatens lives. The most challenging issue is the reduction of climate change and the conversion of the dryland regions into non-dryland regions. Many scientists have designed models for quantifying the impacts of climate change at local, regional, and national levels. The most agreed solution is the adoption of sustainable-based technologies to reduce climate change and increment the non-dryland regions.

## 3.2 Impact of Climate Change on Dryland System

The adverse impacts of global climate change on dryland agriculture are already being felt by farmers around the world. Climate change is projected to have a number of impacts on dryland agriculture, including changes in precipitation patterns, increased temperatures, and increased frequency and intensity of extreme weather events. Changes in precipitation patterns are likely to result in more frequent and acute droughts, which will have a detrimental effect on crop yields and livestock

**Table 3.1** Awareness of respondents about the impact of climate change under dryland agriculture

| Indicators | Percentage of respondents |
|---|---|
| Yield reduction | 76.67 |
| Pest and disease infestation | 74.44 |
| Crop failure | 86.67 |
| Net income reduction | 86.67 |
| Soil moisture evaporations | 71.11 |
| Climate change and rainfall patterns | 83.33 |
| Increase of unsuitable land for cultivation | 64.44 |

Source: Angles et al. (2011)

productivity. Increased temperatures will also lead to higher evaporation rates, further exacerbating drought conditions. In addition, these irregular weather events are likely to become more recurrent and intense, causing damage to crops, infrastructure, and livelihoods (Challinor 2009).

Drought and erratic rains are becoming more common, and crop yields are declining as a result. In some regions, farmers are being forced to abandon their land entirely as the climate becomes too harsh to support any agriculture at all. In addition to the direct impacts of climate change on dryland agriculture, the indirect impacts are also caused for concern. As global temperatures rise, pests and diseases are able to spread to new areas, attacking crops and livestock. This puts even more pressure on farmers who are struggling to adapt to the changing climate. For this reason, farmers will need to adopt new production practices and technologies to manage the changing conditions.

Angles et al. (2011) conducted an experiment at the Dharmapuri district of Tamil Nadu to identify the issues faced by dryland farmers from the impact of climate change. For this they selected 90 respondents through the multistage random sampling design. The data revealed that nearly 87% of respondents agree that their net income is reduced over the years, 83% noticed that there is a change in climatic pattern, 77% admitted that there is a reduction in yield, and 74% are dealing with heavy pest and disease problem (Table 3.1).

The impact of climate change on dryland agriculture is not just economic – it is also social and political. Small-scale farmers in particular are struggling to adapt to the new conditions, and many are being forced into poverty or even starvation. In some parts of the world, this is leading to social unrest and even conflict. The situation is only likely to get worse in the future as the effects of climate change intensify. Dryland agriculture is vital to the global food supply, and the impact of climate change on this sector could have devastating consequences for millions of people around the world. There are three approaches used to analyze the variability in crop production (Fraser et al. 2011):

- Socio-economic framework: This approach mainly emphasizes the political and socio-economic aspects of social or individual groups which differ in terms of the resources available like level of education, the status of health, etc.

- Biophysical framework: This approach helps in identifying the level of damage due to environmental stress on biological systems as well as on social systems and is usually identified by the vulnerability assessment. For example crop simulation models which help us in analyzing the impact of changing climate on crop yields.
- Integrated framework: This will include both the principles of biophysical as well as socio-economic aspects to determine vulnerability. This will be accomplished by taking adaptive measures and policy reforms.

## 3.3 Need of Vulnerability Assessment

Agriculture is an essential component of any society, and it contributes to the food supply, the economy and, in some cases, the cultural identity of a country. Climate change is likely to have a severe impact on agriculture and its practices, especially in dryland areas. Research on future changes in agricultural practices is still in its embryonic stages (Eigenbrode et al. 2018). A vulnerability assessment for dryland agriculture under changing climate is an important step in the process of understanding how climate change will affect dryland agriculture.

Climate change is gradually altering the landscape of dryland agriculture. This is especially true in arid zones, where drylands provide one of the most important ecosystems for human subsistence. Dryland agriculture, however, puts extreme pressure on vulnerable ecosystems. In India, dryland covers about 68 percent of the total cultivated land which influences nearly 44 percent of the total food grain production. Geographically this area includes northwestern part of Rajasthan, Yamuna Ganga alluvial river basins, central plateau region of Madhya Pradesh, highlands of Maharashtra, Tamil Nadu and Gujarat, and Deccan Plateau of Maharashtra and Andhra Pradesh (Vijayan 2016). There is an urgent need to understand the vulnerability of dryland agriculture in the context of climate change. Vulnerability assessment helps to identify the possible risks of climate change that might affect dryland agriculture. This can help to plan for and mitigate the risks. One way that vulnerability assessment helps to plan for and mitigate the risks is by using crop insurance, which helps to reduce the risks of climate change.

Vulnerability assessment is the process of identifying opportunities and threats that an area may face in the future. Under changing climate, vulnerability assessment is becoming critical for dryland agriculture. The need for vulnerability assessment for dryland agriculture under changing climate is for the purpose of implementing appropriate adaptations to the changing climate. This assessment will include a detailed analysis of the vulnerabilities of the dryland agriculture systems and the development of appropriate adaptation strategies.

Ashalatha et al. (2012) also conducted one experiment with a similar trend to Angles et al. (2011), in Dharwad district of Karnataka with 250 respondents. The data reveals that the main reason for reduction in yield is the uncertainty in rainfall which comprises 92 percent of the total respondents. Pest and disease infestation is also increased due to climate change which also is the reason for yield and revenue reduction as shown in Table 3.2.

**Table 3.2** Indicators for yield and revenue reduction due to the impact of climate change under dryland agriculture

| Indicators | Percentage of respondents |
|---|---|
| Alteration in seasonal and temperature patterns | 42.22 |
| Rainfall | 92.22 |
| Pest and disease infestation | 72.22 |
| Degradation of soil fertility and erosion | 46.67 |

Source: Ashalatha et al. (2012)

## 3.4 Dryland Agriculture Implications under Climate Change

The condition of the atmosphere which is beyond the normal either in temperature or the gaseous compounds is climate change. It may be due to an increase or decrease in the temperature and the addition or removal of gaseous compounds. Today's climate change is due to the addition of solar trapping compounds which rising the atmospheric temperature. The environmental components are directly and indirectly dependent on temperature. Depending on the landscape and climate of a region, the rising temperature has positive or negative impacts. The drylands occur where elevated temperature regions have less weathered soil particles due to constraints of water and less organic matter content thereby supporting less vegetation. With rising temperatures due to climate change, the drylands are prone to desertic regions. The available water in the drylands evaporates from the soil pores, and severe wildfires occur which destroy the slow-growing trees and shrubs and higher the chance of fast-growing grasses dominating the region. Moreover, the litter of the soil surface and soil organic matter are also destroyed leading to poor soil health. The soil supports for agriculture and forestry is almost negligible in this dryland region affected by climate change. However, it covers half of the earth's surface land and is settled by 38% of the world's population (Huang et al. 2017). The contribution of the dryland region to livelihood is enormous. Erroneous acts of industrialization, conventional agriculture, transport, mismanagement of land, etc. lead to climate change which affects the environment and threatens livelihood. Moreover, climate change-affected dryland regions render to loss of biodiversity. The environmental cycles, i.e., the hydrological cycle and nutrients cycle (carbon, nitrogen, phosphorous, and sulfur), are disturbed thereby the existence of the vegetation, microbes, and higher organisms. The reason for converting non-dryland to dryland and to desertic regions is human-induced climate change. A proper understanding of the cause of anthropogenic climate change and its impacts and managements is the only solution to mitigate climate change and control the increment of dryland areas.

## 3.5 Drylands' Vulnerability to Climate Change

The dryland regions are facing disruption of the hydrological cycle rather than rising temperatures (Thomas 2008). The erratic rainfall pattern renders the crop production system discouraged. There exists a malfunctioning ecology under climate change. Many strategies have been established for drylands to adapt to the changing climate including the following.

### 3.5.1 Crop Rotation

Monocropping renders poor soil health as the uptake of the same nutrients each year or cropping system exhausts the nutrients. This also imbalances the nutrient ratio into toxicity or deficiency of nutrients. The cropping system like cereal legume is the most prominent system for soil health. Cereal crops are known as nutrient-exhaustive crops, and legume crops have atmospheric N fixation potential. The cereal crops required more primary nutrients (N, P, and K) as compared with the legumes. The nutrients exhausted by cereals are regained by the legume crops and maintaining the nutrient ratio in the soil. Not only the soil's chemical properties are enhanced but also the soil's physical and biological properties. In the context of dryland soils, there is already poor soil health due to unfriendly precipitation, temperature, and soil condition of crops. The introduction of a cropping system that maintains the nutrients cycle and enhances the soil properties without compromising productivity is a promising approach in dryland regions under climate change.

### 3.5.2 Residue Management

The crop residue content nutrients uptake from the soils. With a lack of knowledge, residues are considered waste materials. It is either burnt or removed from the fields which reduced the soil's nutrient level and soil properties. The burning of residues induced climate change. Eastern India is facing climate change due to the burning of cereal residues. This pollutes the air, decreases soil properties, and induces global warming into climate change. A new approach is the return of crop residues after collecting the economical yields. However, different crops have different C/N ratios. The cereal residues have a wide C/N ratio as compared with legume crops. The incorporation of residues should be in a way that does not hamper any crop productivity and disturb the soil conditions (Lawrence et al. 2018). It helps the dryland regions to prevent climate change impacts as it develops the soil's physical, chemical, and biological properties in an optimum condition for plant growth and development.

### 3.5.3 Water Management

The erratic and irregular nature of precipitation defines dryland regions. The management of a drop of rainfall matters in this region for cultivation. Irrigation is the main source of water for crops. Engineering-based irrigation sources such as canals, tanks, and dams are constructed. Due to its high cost, farmers cannot construct whenever required instantly without government support. The site conservation of rainfall is the most effective, i.e., half-moon shape, terrace, mulching, etc. As water is the primary source of cultivation, water management in the dryland regions provides chances for cultivation which facilitates the region against climate change impacts.

### 3.5.4 Conservation Agriculture

Tillage in drylands is disastrous in the soil conditions. It renders soil erosion due to water and wind agents destroying the optimal soil conditions. Since the experience of soil and air disasters due to conventional farming, conservation farming is a promising approach in drylands. It includes reduced, minimum, or no tillage, incorporation of residues, and soil mulching. Conservation farming reduces soil exposure to erosions, enhances soil-water infiltration, aggregates stability, optimizes soil temperature, and reduces runoff under mulching. It also enhances the accumulation of organic matter.

### 3.5.5 Germplasm

The selection of crops based on climatic factors, soil types, and topography facilitates proper plant growth and development. The growing of water stress-resistant varieties is the best option for dryland regions. It depends on the availability of water at the critical stage, the duration of crops, good rooting crop varieties, and the capacity to uptake nutrients. Mainly pulses, oilseeds, and plantation crops are favorable in the drylands.

### 3.5.6 Participatory of Locals

Many strategies and methods have been adopted from the laboratory for farmers' dryland practices. Due to farmers' belief in their own indigenous practices, it is difficult to convince of any innovative ideas to combat climate change. The participation of each person or community, district-wise, and at state and national levels, is mandatory to succeed in dryland cultivation under the changing climate. The scientifically proven technologies and methods that possibly grow crops with minimum requirements without compromising productivity and little contribution to climate change should be followed. The support of the government based on a large project is required. In return to maintain and function properly, the localities play a role. Success to combat climate change in drylands can only be possible when giving hands to each other (Rama Rao et al. 2013).

### 3.5.7 Participatory Plant Breeding

Through conventional and modern plant breeding methods, an ideal plant type, i.e., ideotype can be developed for the target environment through selection for specific adaptations and involving the participation of farmers to overcome some problems with fitting crops to the wide range of target environments.

### 3.5.8 Changes in Cropping Patterns

In the medium term (up to 10 years), efforts should be focused on assisting the farmers in coping with and adapting to climate change rather than attempting to anticipate in greater detail how climate change will affect agriculture or how to reduce greenhouse gas emissions from agriculture. Use of early sowing, short-duration crops, and crops that are more tolerant to heat, salinity, and drought can adjust to climate change.

### 3.5.9 Carbon Sequestration and Increased Resilience of Soils

Climate change is induced by the anthropogenic activities that release GHGs that seal the incoming solar radiation, thereby causing global surface temperatures to increase. Land degradation is another aspect to climate change. This can be mitigated by reducing the GHGs in the atmosphere. The strategy to reduce the atmospheric $CO_2$ in dryland soil is to make sure first of good soil health for net plant productivity.

## 3.6 Conclusion

Dryland agriculture is practiced in areas that receive less than 20 inches of rain per year. These areas are generally found in the semi-arid and arid regions of the world with little or no surface water. Such areas cover almost one third of global land area and have high potential to increase food production if they are managed appropriately. The arid and semi-arid regions, where dryland agriculture is predominantly practiced, are highly sensitive to climate variability and change. The changing climate poses an imminent challenge to dryland farmers who practice a wide range of techniques from traditional methods to advanced irrigation systems for crop production. Drivers of vulnerability in dryland agriculture include limited surface water availability, inter-annual variability in rainfall and extreme rainfall events, water quality and salinity, soil degradation, and climate-sensitive diseases and pests.

Infrastructure, such as diversifying cropping patterns, investing in on-farm water harvesting, and developing multiple cropping systems, could help in enhancing the resilience of dryland agriculture. Produce using renewable resources, such as relying on indigenous water harvesting techniques and reducing emissions and increasing carbon sequestration, could also help in reducing the impacts of climate change.

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# Climate Risk Management in Dryland Agriculture: Technological Management and Institutional Options to Adaptation

# 4

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## Abstract

Recently, climate risk is a crucial problem behind a majority of global issues in the twenty-first century. Dryland agriculture is also known as risky agriculture because of its basic features of being vulnerable to drought and others climate risks. Sustainable growth in dryland agriculture is urgent to meet various goals of a country like poverty reduction, nutritional requirement, and food security. Climate risk in dryland agriculture is aggravated due to the poor resource base and biotic source threats that lead to production risk. Technological management practices, policy solutions, and institutional adoption are the considerable way to overcome the climate risk in dryland agriculture. Moreover, there is a need to be strengthened the existing technological, institutional, and policy solutions by integrating all management options and their implementation at ground levels through various research organizations. A complete and proactive combination of technological, institutional, and policy solutions is the only way to manage the

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climate risk at village, block, district, and national levels. Research organizations or institutes are monitoring management solutions and executing capacity-building programs (social protection programs, Village Climate Risk Management Committee) and providing services such as Agrometeorological Advisory Services to reduce the climate risk at the community, district, and national levels.

**Keywords**

Dryland · Climate risk · Technology · Management · Institutional options

## 4.1 Introduction

In the twenty-first century, climate risk is a major issue in dryland areas, and the main cause of risk is climate variability at the global level. Numerous researchers have done work on technological management and institutional adoption to overcome the risk in the past ten years. In this connection, they observed technological and institutional options can increase and stabilize farmer incomes, protect assets from shocks, and finally reduce the poverty in climate risk agricultural lands. Some improved production practices and technologies including diversified production systems, conservation agriculture, and conservation of stress-resistant and tolerant crop germplasm sustain the farmer incomes by stabilizing crop production in risk-prone areas and, consequently, lessen the negative impacts of climate risk to some extent under some conditions. Institutional options like index-based insurance and social protection along with technological management play supportive roles for farmers to protect their resources against the adverse impacts of climate variability and manage the risk-related barriers in dryland agriculture.

Climate risk such as drought is one of the most crucial natural factors that cause famine and malnutrition at the global level. There is a need to protect the vulnerable areas from climate variability or climate-related risk by adopting technological management practices and institutional options. A complete and proactive combination of technological, institutional, and policy solutions are the only way to manage the climate risk at the village, block, district, and national levels. There is a demand for more research to identify climate risk-affected regions and farming communities and improve risk management practices and institutional options to stabilize the rural people’s income and reduce poverty. This study reviews the qualitative and quantitative approach to mitigating the climate risk in dryland areas using improved technological management practices and institutional options for adaptation at the local level.

## 4.2 Climate-Resilient Technologies in Dryland Agriculture

Adverse impacts of climate change on agriculture are being witnessed all over the world, but countries like India are more susceptible in view of the increasing trend of population dependent on agriculture, extreme pressure on natural resources, and poor coping management practices. The projected impacts are likely to further increase field fluctuations of many crops and, thus, impacting food security. Significant negative impacts have been projected with medium-term (2010–2039) climate change, e.g., reduction of crop production by 4.5–9%, depending on the magnitude and distribution of the detrimental effect of global warming and climate change. Since agriculture makes up roughly 15% of India's GDP, a 4.5–9.0% drop in production implies roughly at 1.5% of drop in GDP per year (Kumar et al. 2018; Srivastav et al. 2021). Further, climatic discrepancies may affect the natural resource availability and management, energy resources, temperature, agricultural productivity and sustainability, annual rainfall pattern, as well as soil and human health (Aggarwal et al. 2019; Singh et al. 2021a, b; Mukherjee et al. 2021).

However, an increase in crop yield is considered as the major route for addressing future global food demand, through increased potential yield (maximum yield with best varieties and agronomy and removing constraints) and meeting up the gap between actual farm yields and potential yields (Fischer et al. 2009). The "drylands," covering about 0.41 of the Earth's land surface, will need to contribute the share of this part if we have to achieve sustainable yield increase in future days (Carberry et al. 2011). These dryland areas are limited by soil moisture resulting from low rainfall and high evaporation and can contribute in increasing primary productivity, ranging from hyper-arid, arid, and semi-arid to dry subhumid areas based on the moisture deficit conditions (Carberry et al. 2011). As India is one of the most drought-prone countries in the world, about 53% of the country's geographical area comes under arid and semi-arid region. The drylands of semi-arid areas of central India are more drought-prone compared to the other parts where 45% of country's agriculture production comes from these drylands. But it was reported that about 330 million people were affected by drought during 2015–2016 (Rao et al. 2016; Samuel et al. 2021). This is because the productivity of crops grown here is heavily dependent on the climate and monsoon rainfall. The frequency and intensity of droughts are also growing, posing challenges to the crop productivity of these areas due to climatic aberrations (Rao et al. 2016; Kumar et al. 2018; Singh et al. 2021a, b; Samuel et al. 2021). Therefore, enhancing agricultural productivity particularly for the dryland areas is critical for ensuring food and nutritional security for all. Here is the need of the adoption of agriculture technology like climate-resilient agricultural (CRA) practice that can tackle irregular climatic variations.

The concept of "resilience" has been recognized as an important policy perspective within sustainability science and development paradigm (Adger and Kelly 1999; Hansen et al. 2019). The CRA practices will address risk and how droughts can be efficiently managed by developing the resilience of the agroecosystem as a whole through CRA. In India, there have been changes in the developmental policies to make the capacity of systems to manage climate risks more typically (Srivastav et al.

2021; Samuel et al. 2021). To address the effects of extreme weather events such as drought and to have sustainable adaptation strategies at farm level, the government of India developed the concept of a climate-resilient village (CRV) through the network program of the National Initiative on Climate Resilient Agriculture (NICRA), which is considered as the largest outreach to the local communities in climate change scenario. The project was initiated by the Indian Council of Agriculture (ICAR) and the Ministry of Agriculture and Farmers' Welfare (MoAFW) during 2011, and the second phase (commenced in 2017) is called National Innovations in Climate Resilient Agriculture (NICRA) (Samuel et al. 2021). The climate-resilient practices listed by the NICRA for dryland agriculture are classified under four main categories: natural resource management, crop production, livestock, and institutional interventions (Kumar et al. 2018). The category natural resource management contained practices like in situ moisture conservation practice, biomass mulching, incorporation/retention of crop residues into the soil instead of burning, brown and green manuring, rainwater harvesting, proper drainage, minimum soil disturbance, conservation agriculture, organic agriculture, artificial groundwater storage, and water-saving irrigation methods. Climate-resilient crop production practices consisted of drought-/temperature-tolerant varieties, water-saving paddy cultivation practices, community nurseries on multiple dates, farm machinery custom hiring centers, location-specific intercropping systems, and crop rotation. Uses of community lands for fodder production, improved planting material, improved fodder storage, fodder enrichment, prophylaxis, and heat stress-reducing shelters for livestock are included under resilient livestock management practices. Institutional interventions for climate resilience included the constitution of a seed bank, fodder bank, commodity groups, custom hiring center, collective marketing group, weather index-based insurance, and climate advisory. These practices are found to be operative in solving ground level problems generally faced by the farming community as well as for facilitating satisfactory economic assistances (Biswas et al. 2015; Niranjan and Bose 2015; Singh et al. 2021a, b). The technologies that can be adopted in drylands under CRA practice are (Alvar-Beltrán et al. 2021) the following:

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| Agroforestry | Practicing agroforestry can minimize the emission of greenhouse gases (GHGs) from the agricultural field by C sequestration<br>Developed root systems can reduce soil erosion and improve soil health by increasing soil organic matter, nutrient availability, and microbial activity<br>Leaves from trees enrich the soil and help keep soil moisture, contributing to efficient and self-sufficient use of water<br>Crop cover reduces evaporation from the soil due to direct sunlight and by decreasing air and soil surface temperature<br>A range of benefits also severed by agroforestry to our environment in regular basis includes sustainable firewood, timber, fodder for animal feeding, and medicinal uses |

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|---|---|
| Agronomic practices (e.g., weeding, harrowing, grafting, mulching) | Weeding and defoliation reduce soil water losses caused by plant transpiration<br>Cover crops reduce rainfall striking effect on soil and also minimize soil erosion by increasing soil organic matter along with water, air, and nutrient availability<br>Breaking the soil into small fragments (harrowing) can prevent the loss of land moisture by evaporation<br>Recycling water resources through hydroponics can reduce water losses. Covering the soil with crop residues (mulching) in combination with no-tillage reduces the exposure of crops to heat-stress conditions. It also increases soil moisture by reducing direct soil evaporation |
| Half moons | Improve the use efficiency of fertilizers by adding the needed nutrient amounts to a planting hole instead of spreading them over the entire field area by broadcasting<br>Reduce soil erosion and increase macronutrient deposition and infiltration by reducing surface runoff |
| Zaï pit systems | Improve the efficiency of fertilizers by adding the required amount of nutrients to a planting pit instead of spreading them over the entire field area<br>Increase water infiltration rates as water is trapped in the pits close to the root systems of crops<br>Protect the main stem and branching system of crops by reducing the area exposed to strong winds |
| Terracing | Reduces soil erosion and increases macronutrient deposition and infiltration by dropping surface runoff |
| Drought-tolerant crops (e.g., sesame, millet, sorghum, quinoa) | Crops with low water requirements reduce evapotranspiration losses during photosynthesis by closing their stomata quickly and can maintain optimum turgor pressure in plant cells<br>Enhance food production during the dry season when food insecurity levels are highest |
| Drip irrigation systems | Increase water-use efficiency by providing sufficient water according to the crop<br>Partial root zone drying maximizes water-use efficiency by adding water only on half of the root zone<br>Reduce soil erosion and macronutrient losses from leaching<br>Promote weed control as water is locally applied<br>Reduce the risk of diseases that occur under damp conditions |
| Programmed irrigation | Uses water resources more efficiently and avoids permanent wilting point as well as field capacity<br>Reduces losses from direct evaporation by providing water when evaporation rates are lowest (dawn and/or dusk)<br>Promoting irrigation at dawn and dusk reduces direct soil evaporation, making better use of water resources. |

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|---|---|
| Reuse of treated waste water, desalinated water | Brings additional nutrients to the plants and enhances yields<br>Increases water-use efficiency and promotes sustainable withdrawal and supply of freshwater to address water scarcity |

## 4.3 Seasonal Climate Forecasts (SCFs) for Climate Risk Management in Dryland Agriculture

Seasonal climate predictions have been already shown to bring added value for agricultural decision-making in several regions of the world (Falloon et al. 2018; Iizumi et al. 2021; Ceglar and Toreti 2021). Despite the potential farmers' benefits of seasonal forecasts12, they have been faced with many challenges in adequately responding to end-user expectations, associated with lower prediction skills in several key regions (such as Europe) and the dependency between the skillful forecast time and the spatial scale of relevant climate events (Van Den Hurk et al. 2016). SFC can be done by using different simulation models to minimize climate fluctuations. For an example, the simulation methodology for seasonal soil water forecasting for Australian dryland cropping systems was done by a group of researchers (Western et al. 2018) with a large number of samples. This study was undertaken for a pilot assessment of the potential to extend seasonal weather outlooks to plant-available soil water (PASW), and they analyzed 20 sites in the southeast Australian wheat belt using seasonal weather outlooks from the Predictive Ocean-Atmosphere Model for Australia (POAMA, (the operational seasonal model of the Australian Bureau of Meteorology), which were downscaled and used in conjunction with the Agricultural Production Simulator (APSIM). The sensors were installed in August 2012, but the deeper sensors (60–120 cm) only provided reliable data after the major wetting event in June 2013, just after the wheat was planted. From June 2013 onward, the response the model tracks the observed profile plant-available soil water content within ±20 mm for wheat and ± 40 mm for canola, and there is very good consistency between APSIM and the observations. The larger errors for canola are due to the model lagging a little behind the spring growing season dry down. Overall these results give reasonable confidence that APSIM represents soil water dynamics satisfactorily.

## 4.4 Climate Risk Management Approach for Climate Adoption in Dryland Agriculture

There have been some of the most studied theories to avoid drought, i.e., drought avoidance, drought resistance, and drought tolerance. Some of the strategies to adopt such mitigative strategies are:

- Better preparedness to withstand drought.
- Development of a more resilient ecosystem for faster recovery from drought.
- Mitigate the impact of drought.

This means the strategies must be focusing on planning such crop management practices which will be least affected by the occurrence of drought and, if faced with drought, can recover from its deteriorative effects easily and regain their original property.

To achieve the above scenarios, there must be integrated agroclimatic management aspects which can be done through shifts in the agricultural systems which include geographical shifts as well as crop combination shifts, climate-proof crop management, and irrigation planning systems.

### 4.4.1 Shift in Agricultural Systems

The regions that at present fall under subhumid climate are gradually starting to experience arid climates; thus the moisture conservation and irrigation practices must be adapted accordingly. Shifting from more water-demanding crops to less water-demanding crops like coarse millets, heat-tolerant crops can be a suitable shift in crop for potential drought management.

### 4.4.2 Climate-Proof Crop Management and Irrigation Planning Systems

Manipulation of crop rotation to less water-demanding crops can be a manifestation of less pressure on available water, inclusion of legumes in rotation, changing crop calendar, selection of low duration crops as well as some of the crop improvement, and moisture conservation practices like conservation agriculture and integrated nutrient management, promoting agroforestry or agropastoral systems.

The climate-proof irrigation planning system includes some of the strategies to improve water-use efficiency like drip and sprinkler irrigation systems, making potential use of rainwater through water-harvesting structures, intermediate use of rainwater as well as irrigation water, treatment of sewage water, and its judicious application in crop production.

### 4.4.3 Crop Management Aspects

#### 4.4.3.1 Crop Diversification (Crop Rotation, Intercropping, and Agroforestry)

Scanty and lack of timely rainfall are the two main reasons for inefficient crop growth and productivity in dryland regions; however, the financial loss due to complete failure of one crop can be managed by adopting crop diversification in which the alternative crop in rotation can generate some income. It can stabilize net return even under uncertain climate change scenarios because if one crop fails, the other crop can give some earnings. But the selection of crops should again be done according to the climatic suitability (less water wanting, crops with less transpiration, high temperature-tolerant) condition. Intercropping and mixed cropping are other two ways of insurance from drought stress. Finger millet + pigeon pea and finger millet + black gram and foxtail millet + pigeon pea are some of the common and profitable intercropping systems in drylands. A study conducted by Manjunath et al. (2018) intercropping of soybean + foxtail millet (row proportion of 2:1 and 4:2) recorded higher B/C ratio (2.39 and 2.45, respectively). Along with the common benefits of improved soil fertility, reduced soil erosion, moisture storage, and utilization, reducing occurrence of crop pest, the cereal legume intercropping in drylands provides food, nutritional, and economic security to the growers and the population there. But again, the resource endowment through intercropping in dryland depends on the land area, excessive scanty moisture availability, irrigation facility, and the crop's capacity to utilize soil moisture and nutrients (Bantilan and Aupama 2006).

Agroforestry can be a solution for ensuring productivity and returns of farmers. The agrihorti-, silvipastoral, agri-silvi-horti- and agroforestry systems are helpful in reducing the erosion of soil which is very predominant in arid and semi-arid regions. Selection of nitrogen-fixing trees and continuous litter addition to the soil from the tree species can increase soil fertility, does not allow water erosion, and can also support moisture storage to some extent. Again, these species are helpful in ameliorating the salt-affected soils of arid regions. For example, as per an observation by Singh et al. (2014), *Prosopis juliflora-Leptochloa fusca* silvipastoral system reduced the soil pH and electrical conductivity and increased the organic carbon, available nitrogen, phosphorus, and potassium contents. It can also be utilized for biofuel and bioenergy production, e.g., *Jatropha curcas*, *Pongamia pinnata*, *Simarouba*, *Azadirachta indica*, *Madhuca indica*, etc. are some of the trees borne oilseeds which can be used for bio energy production. The benefits of agroforestry system are boundless. Above all these systems are obvious sources of food, fodder, timber, and many other valuable products like lac, honey, medicinal plants, and fruits.

#### 4.4.3.2 Suitable Crop Species (Millets and Pulses)

The crops resilient to extreme temperature are selected because of their higher harvesting index and water-use efficiency under such conditions. For example, as per a study conducted by Jat et al. (2012), pigeon pea and sorghum are more resilient to drastic climatic impact of drylands than maize and wheat.

The wild variety of crops also possesses certain potential genes which can be exploited in future to develop suitable varieties for dryland areas because of their adaptability to drought and heat stresses (Solh and van Ginkel 2014). The pressure due to increasing human population and herds of animals is on the fragile natural resources which are gradually destroying the wild species of modern cultivars. Thus, it is essential to preserve the wild germplasms for mitigating future climate scenarios. Legume crops are also suitable for dryland regions because of their low water requirement, short duration of growth, better nitrogen-fixing capacity that supports soil fertility, and nutrient availability to the succeeding crops. For example, lentil and chickpea can be grown at low rainfall levels of 250–300 mm, but fava beans require more, i.e., 450 mm and above. Thus, legumes in dryland have both aboveground and belowground benefits.

As dryland area of the world is surging into other agroecological regions because of increased climate change scenario, the agricultural practices to cope with untimely and scanty rainfall scenario should be chalked out in advance. The farmers can go for diversified income sources instead of focusing only on cropping, which can save their socio-economic condition. For example, farmers can go for livestock production like goats, poultry, and cattle; trading of value-added products from farm produce and brick production can be taken up as well (Bantilan and Aupama 2006).

#### 4.4.3.3 Conservation Agriculture

A mitigative resource conserving land management practice known as conservation agriculture can be adopted. It constitutes three main principles of reduced tillage, permanent organic mulch, and crop diversification. Reduced soil disturbance and organic addition are suitable ways to conserve moisture in the soil profile by reducing the rate of evaporation, giving higher opportunity period for water infiltration.

### 4.4.4 Water Management Aspects

#### 4.4.4.1 Judicial Irrigation Practices

Scarcity of moisture in the soil profile and lack of irrigation facility are the two important constraints of dryland agriculture. Even the growers are less aware regarding scheduling irrigation in a proper manner (deciding the frequency and depth of irrigation water requirement for the crops). As drylands experience less amount of rainfall for a short duration and the high heat of the area causes high rates of evaporative loss, it is essential to use the irrigation water most judiciously. To improve the water-use efficiency of crops, it is always essential to plan precise irrigation schedule during the critical crop growth stages mostly flowering and grain-filling stage. In water-scarce condition, the supplementary irrigation during critical stages can boost productivity and biomass harvest. For example, a study cited by Solh and van Ginkel (2014) showed that limiting water supply in the beginning of the season and giving supplemental irrigation during flowering and grain-filling stage doubled the productivity as compared to the conventional approaches. Precise water application can also be done through drip irrigation and sprinkler irrigation facility which can not only increase the water-use efficiency but also decease the pressure of water erosion and leaching losses.

#### 4.4.4.2 Rainwater Harvesting

Along with supplied water, the natural source of water, i.e., the rainwater can be utilized to optimize production through water-harvesting structures. The runoff water from different land surfaces is channelized to be collected into a small artificial catchment placed at a slight lower elevation from which channels are again prepared to irrigate crop fields, tree plants, and shrubs.

## 4.5 Technological Interventions for Climate Risk Management in Dryland Agriculture

In view of climate change scenario, feeding the ever-increasing human population aside highly degraded natural resource base (particularly, soil, and water) needs improvisation in the current practices of crop cultivation in dryland agriculture. Ensuring food to the ever-burgeoning population on a sustainable manner necessitates the development of suitable long-term coping strategies in the dryland agriculture. Currently, farmers have quiet known about adopting the climatic stresses by resorting to diverse management practices, viz., multiple cropping, selection of suitable varieties, pre- or postponing the planting times, and, thus, by expanding their income sources (Chimwamurombe and Mataranyika 2021). However, these farmers' friendly climate adaptation strategies must be improvised with new innovations to cope with the climatic stresses in near future. Below are discussions on the technologically intervened strategies combined under three heads for the purpose of climate risk management of dryland agriculture:

### 4.5.1 Shifting to Resilient Crops and Adapted Varieties

For a successful adaptation against climatic variabilities in dryland agriculture, identifying region-specific climate-resilient crops and varieties is paramount. In a simulation study in the semi-arid regions of Zimbabwe with APSIM model, Dimes et al. (2008) have observed that pigeon pea and sorghum showed more resiliency to the climatic stresses over the maize and groundnut. This was primarily associated with improved harvest index of pigeon pea and water utilization ratio of sorghum, respectively. Here, the pigeon pea is a long-duration crop with its grain-filling phase overlapping with rainfall-deficient, water-stressed period. But higher temperatures under climate change scenario will curtail its growth period, and, thus, it will give the fruit when the wet season is still there. On the other side, such shortening of crop growth duration is greater in vegetative phase of sorghum (by 18%) compared to the grain-filling phase (by 14%), which results in an improved harvest index. It indicates that retargeting the currently practiced long-duration crops and its varieties to the regions where climate change led increase in temperature is likely to happen may prove to an easy and readily adaptable option to endure climatic risk in drylands.

### 4.5.2 Improvisations with Agronomic Interventions

Under the threat of climate change, crop cultivation relying on the existing conventional practices may no longer be pertinent. Therefore, recommendation of adaptation technologies to the farmers for climate-resilient crop management is in prime need. In this background, ICRISAT has recommended many strategies, viz., cultivating day-neutral, early maturing, high aboveground biomass-producing varieties with optimal root traits and lenient to diverse biotic and abiotic stresses, crop residue mulching, increased number of seedlings per hill for heat tolerance, better soil nutrient and water-use efficiency, conservation of water monsoon deprived period, and supplemental irrigation with harvested rainwater short-duration drought to derive positive effects of the increased $CO_2$ level to manage climate change and variability impacts on dryland agriculture (Zúñiga et al. 2021). Due to low organic matter status of dryland soils, emphasizing strategies to improve soil organic carbon would be a paramount driving force for increasing biological activities and nutrient cycling in soil. Besides, enhancing organic matter in soil can reduce the climatic variability-induced poor water use of crops by increasing the soils' water-holding capacity. Therefore, strategies to enhance and maintain soil organic carbon need to be implemented. Bunds surrounding the agricultural fields can be utilized for growing nitrogen-fixing grasses, shrubs, trees, etc. that could be used as ex situ green manuring. Raising *Gliricidia* sp. at 75 cm spacings on such bunds has been reported to supply organic matter and 28–30 kg nitrogen per ha. Besides this, farm-derived organic residues can be composted or manured to use as sources of plant nutrients and organic carbon (Wani et al. 2005).

Another strategy that is currently being promoted for climate change adaptation is conservation agriculture. Conservation agriculture involving zero−/minimum tillage, crop residue cover, and diversified crop rotations may show climate resiliency besides providing sustainable crop yields through natural resource (mainly land and water) conservation and other linked ecological benefits. Increase in average cereal yields (by 1.5–3 times) in greater than 40,000 farm households through conservation agriculture have been reported in Zimbabwe (Twomlow et al. 2008). In ICRISAT also, conservation agriculture has been proved to enhance crop productivity and soil quality beside significant mitigation in water runoff and soil loss (Jat et al. 2012).

Crop diversification by inclusion of legumes, tree species of multifarious utilities, plants with medicinal and aromatic values, etc. may help acquire adaptation against climate change shocks in dryland agriculture. In model watershed, intensification and diversification of cultivation with high-utility crops provided basic staples to the farmers along with surplus of farm incomes (Wani et al. 2011) when rice and rapeseed cultivation was intensified along with livestock (pig-raising) and horticultural crops (vegetables like beans, peas, sweet potato, etc.) and groundnut (Wani et al. 2009; Jellason et al. 2021). Accordingly, identification of suitable region-specific crop diversification options under various agroecological regions is necessary. In this background, ICRISAT is already in motion to identify resilient crops and cropping combinations through its watershed program in across India.

### 4.5.3 Robust, Planned, and Integrated Watershed Management

Under the climate change scenario, the most of the precipitation will now occur as high-intensity short-spelled events (IPCC 2007). Harvesting the runoff water is thus a prescribed option for crop protection against water stress as well as avoidance of floods in lowland areas. Therefore, integrated watershed management would be important for soil and water conservation and boosted crop and livestock productivity in dryland areas. A consortium model proposed by ICRISAT for efficient watershed management highlights the principles of collective action, convergence, cooperation, and capacity building (4Cs) to deal with the issues of equity, efficiency, economics, and environment (4Es)(Wani et al. 2009). The new watershed model emphasizes on the technologies to manage runoff water, water harvesting for supplemental irrigation, on-field moisture conservation strategies for greater moisture retention, recharge of groundwater, establishing grasses on waterways, suitable nutrient management strategies, and improvised cropping technologies and farming systems, while protecting the environment (Wani 2002; Wani et al. 2006; Sreedevi et al. 2004). However, improved water management alone may not enhance the crop productivity in the dryland areas; thus, the emphasis on proper soil, crop, nutrient, and pest and disease management must not be compromised to boost crop productivity and provide climate change resilience to dryland systems.

In the near future, drylands will become the hub of the nation's food security, and so development of climate change adaptation strategies aside restoration of natural resource base is a priority. This is truer for the millions of the poor populations residing in the arid and semi-arid regions. Accepting and adopting the abovementioned strategies may help dryland agriculture cope with climate change shocks; besides those, the integrated watershed management holds a great promise to curtail the climatic variability impacts on dryland agriculture through natural resource conservation, boosted productivity, and income generation through diverse on-farm and off-farm activities.

## 4.6 Institutional Options for Climate Risk Management in Dryland Agriculture

The mitigation of climate-related risks cannot be achieved by using technologies and management practices alone. Institutional interventions along with technological management practices act as complementary to each other to mitigate climate risk in dryland agriculture. There is an urgent need to improve existing institutional options and technological climate risk management practices to cope with prior and post adverse impacts of climate variability for vulnerable regions. Climate variability can be managed effectively through policy solutions and institutional interventions along with improved technological practices at block, district, and national levels. There is a need to be aware of the negative impacts of climate risks and to examine the institutional capacity in adaptation processes at community levels. The success of institutional adaptation attempts to mitigate the climate risk depends on the essence of existing nonformal and formal institutions at a community level. An understanding of the structures and arrangements of different institutes functioning at national and international levels is important to facilitate risk-mitigating adaptation processes. Public and private institutions at local levels configure the adverse effects of climate-related risk on communities (Agrawal 2010). Institutions including both formal (organizational structures) and informal (tradition and cultural norms) have demonstrative capacity to cope with risk and uncertainty and also facilitate adaptive capacity at the local level (Agrawal 2010; IPCC 2012). The institutional options and policy solution hugely affect the adaptive potential of a group at the local level (Smit and Wandel 2006). In this study, we review the role of institutional intervention, policy solutions, and social protection to manage the climate risk in dryland agriculture and reduce rural poverty. The adaptation and risk mitigation planning are spare on the involvement of stakeholders, expertise in risk-mitigating technology, comprehensive information, and enlightened decision-making.

### 4.6.1 Index-Based Agricultural Insurance

Index-based insurance is mainly based on parameters such as yield, rainfall, temperature, and vegetation remote sensing that are highly correlated with agricultural losses. The purpose of index insurance is to successfully attain livelihood promotion and protection targets. Index insurance aims to adopt new improved technologies, reserve profitable assets, and accelerate speedy recovery after climate variability shocks and retrieving to credit. Initially, livestock-based index insurance is made that protect rancher or cattle man by preserving their productive asset from the extreme climate variability shocks. Janzen and Carter (2013) have reported that index insurance cherished the next-generation human capital for poor farmers with low assets via balance food intake. Many studies have analyzed and reported index insurance which improved the adoption of cost-effective production technologies that was facilitated by garnished access to credit. Carter et al. (2017) observed that farmers are unable to coordinate for securing loans and risk, in such environments, index insurance can be encouraged for the adoption of improved technologies.

Numerous studies showed that index-based insurance has increased the adoption of improved technologies and also increased crop production, wealth buildup, and food security under high climate risk areas (Fuchs and Wolff 2016; De Nicola 2015). Recently, randomized trials and less demand in index-based insurance initiatives are uninformed by recognition which focuses on poor farmers for their speedy scaling up (Cole et al. 2013). To address a group of rural peoples, capacity building of private insurers is needed to get farmers to support through farmers' training. Index insurance reduces the risk of moral hazard, high transaction costs, and payout delays which reduces traditional loss-based crop insurance for farmers.

#### 4.6.1.1 Weather Index-Based Insurance

Weather index insurance protects the farmers in dryland areas against weather shocks such as drought, very less rainfall, and flooding by using indexes like crop yield, weather data (temperature, rainfall, humidity), and historical rainfall (Osgood et al. 2007; Salgueiro 2019; Barnett et al. 2008). It also enhances productivity and provides opportunities to cope with the climate risk in areas with poor resources such as dryland farming/rainfed farming. This index insurance is advantageous to both insurers and small household farmers such as discounts for small household farmers prone to risk, fewer transaction costs, and financial availability to insurers, and also applicable in rural areas (Alderman and Haque 2006; Hellmuth et al. 2009). Yet, in few regions, this insurance is influenced by a lack of awareness among the small household farmers, lack of weather data, and lack of information for microclimates and weather forecasts.

Turvey (2001) demonstrated how weather index-based insurance addressed climate risks by using weather data and historical rainfall data at the community level and how heat and rainfall insurance are costed in the process. Mills (2007) observed that risk management practices that are market-oriented and nonformal insurance are less effective without innovations where climate variability is very high which requires the incorporation of changes in future uncertainty such as weather data. The necessity of a weather index-based insurance contract is to report for such changes to reduce loss contracted at the community level and ignorance of any biases in the payout. The major role of insurers is to pool risks across larger prone areas to reduce the variability in income and for reinsurance (Meze-Hausken et al. 2009; Skees et al. 1999).

### 4.6.2 Village Climate Risk Management Committee

An institute at the village level was formed with Gram Sabha approval that includes all kinds of farmers along with 12 to 20 people with the secretary, treasurer, and president with at least one-woman member elected among villagers (Rao et al. 2016). This committee implements programs, discusses problems related to climate risk-prone areas, and also provides solutions such as the formation of water conservation structures at village levels. In all climate-resilient villages, the Village Climate Risk Management Committee opened a bank account for financial transactions. This bank provides financial support to farmers and for the execution of various activities at community levels.

## 4.7 Social Protection Programs for Climate Risks Prone Areas

Social protection programs play a key role in protecting low household farmers through financial support, social insurance, and labor market programs that are helping unemployed farmers (FAO 2015). Liquidity limitation, ease in credit, and savings can increase production in dryland agriculture by investing in management technology and assets such as farms, livestock, and non-farm (Asfaw et al. 2014; Davis et al. 2016; Fisher et al. 2017a, 2017b; Kabeer et al. 2012). Asfaw et al. (2016) and Lawlor et al. (2019) reported well-organized social protection programs such as

Zambia Child Grant Program capacitate poor farmers to cope with climate- and market-related shocks.

## 4.8 Agrometeorological Advisory Services (AAS)

Agrometeorological Advisory Services play a major role to reduce the losses because of aberrant weather and climate variability by giving information about possible weather conditions in advance. This advanced information on predicted weather conditions may help farmers in choosing crops or variety, deciding farm operations, irrigation scheduling, and protection from drought, frost, and strong wind that increase agricultural productivity in dryland areas (Rao et al. 2016). First weather station services were started by IMD in the year of 1945, and now each state and central agricultural universities have Agrometeorological Advisory Services (AAS). Recently, ICAR has started the All India Coordinated Research Project on Agrometeorology (AICRPAM) which is a web-based spread of agromet advisories at local and national levels for the benefit of farmers (Dupdal et al. 2020). AAS is helping in creating awareness among rural peoples or farmers to adopt weather-based advisories that will give information about weather conditions and improve agriculture production. It has also encouraged farmers for adopting modern technologies and practices such as pest/disease management, modern postharvest technologies, promoting weather-based irrigation management, and commercial marketing of commodities.

## 4.9 Conclusion

Climate risk in dryland agriculture is aggravated due to the poor resource base and biotic source threats that lead to production risk. Enhancing agricultural productivity particularly for the dryland areas is critical for ensuring food and nutritional security at the community, district, and national levels. To combat against climate risks, there is the need of the adoption of climate-resilient agricultural (CRA) practice that can tackle aberrant weather and climatic variability. Technological management practices and institutional adoption are the considerable way to overcome the climate risk in dryland agriculture. There is a need to be strengthened the existing technological and institutional by integrating all management options and their implementation at ground levels through various research organizations.

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# Part II

# Management of Natural Resources

# Achieving Land Degradation Neutrality to Combat the Impacts of Climate Change

# 5

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## Abstract

Beyond natural climate variability, frequent and intense extreme events caused by human beings are the reasons for climate change which lead to adverse impacts, losses, and damages to nature and people. Climate change is a global phenomenon that is occurring continuously since the earth came into existence and has become a major scientific issue during the last decade which is threatening food security. It is influencing soil fertility through alteration in soil moisture, increase in soil temperature, and elevated $CO_2$ levels, which are the major causes of land degradation (changes in the productive potential of the land for human use). Land degradation has become a critical issue worldwide, especially in developing countries. Land degradation is caused by climate change which has significant impacts on agriculture through direct and indirect effects on soils which should be considered more important for modern human societies with increasing populations to meet the global demands for food with limited soil resources. Under these circumstances, the concept of land degradation neutrality is the need of the hour, and it is one of the Sustainable Development Goals required to stop the ongoing land degradation. The three concurrent actions required for achieving LDN are (1) avoiding new degradation of land by maintaining existing healthy land, (2) reducing existing degradation by adopting sustainable land management practices and ramping up efforts to restore them, and (3) returning degraded lands to a natural or more productive state. LDN can be achieved by a paradigm shift in land stewardship from "degrade-abandon-migrate" to "protect-sustain-restore."

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Climate variability · Food security · Soil fertility · Land degradation

## 5.1 Introduction

### 5.1.1 Climate and Soil Interaction

According to the Intergovernmental Panel on Climate Change (IPCC), global average temperatures would likely to climb between 1.1 and 6.4 °C by the year 2090–2099 and are likely to rise between 1.8 and 4.0 °C (IPCC 2007). There will be consequences for the ecosystem, particularly the soil, as a result of this climate change (Brevik 2012). Soils are also important for food security (Brevik 2013a, b, c), and changes in climate effects on soil properties and processes have the potential to jeopardize food security (Brevik 2013a, b, c). Understanding these consequences of climate change and adopting the measures necessitate the knowledge of the interaction between climate and soil. This paper mainly focuses on the interaction between climate and soils, the prominence of C and N cycles, changes in the soil properties, and processes in the context of climate change and the available mitigation options to control or reduce the soil erosion to enhance the food production for future generations as part of food security.

### 5.1.2 Food Security in a Changing Climate

Food security is defined as "a scenario in which all people have physical, social, and economic access to enough, safe, and nutritious food that fits their dietary needs and food choices for an active and healthy life at all times" (FAO 2003). The land acts as a major source for food production which indicates that soils are vital for food production as these soils are integral components of terrestrial ecosystems. The IPCC reports on changes in global temperature and precipitation patterns (Meehl et al. 2007) have already occurred and will continue to occur, resulting in changes in soil properties and processes. This has sparked widespread fear that climate change could jeopardize food security (Sauer and Nelson 2011), resulting in an overall decline in human health.

### 5.1.3 Does the Soil Properties and Processes Influence Climate Change? (Biogeochemical Cycles)

Soil organic matter is the source of carbon and nitrogen which influences the water-holding and ion exchange capacity and nutrient supply to soils (Brady and Weil 2008). Soils were considered to be more productive when it contains sufficient organic matter (Brevik 2013a, b, c). Change in the C and N cycles may affect the soil properties and processes which are closely associated with climate change. The jump in the global temperatures may harm C demarcation in the soil, which results in lower soil organic C and a positive response in the global C cycle (the rise in temperatures leads to an increase of $CO_2$ from soils into the atmosphere, which ultimately leads to increased temperatures) (Gorissen et al. 2004). Decomposing organisms in the soil requires more N. Increases in the C/N ratio are observed as part of the $CO_2$ enrichment that will have the ability to limit N mineralization. Mineralization is a pivotal stage in the carriage of nitrogen to plants (Mullen 2011). If N mineralization is reduced, the plant-available N levels in the soil will get decreased which results in lesser plant productivity. The most important long-lived greenhouse gases are carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$) (Hansen et al. 2007). Burning of fossil fuels, continuous tillage practices, and other human activities have disturbed the natural equilibrium that lead to the increased atmospheric C and N levels that are beyond the absorbance capacity of the global sinks (Pierzynski et al. 2009). The best soil management practices can have notable footprinting maintaining the balance between C and N gases emission from the soils and thus on the global climate change.

### 5.1.4 Soil Carbon Active and Inactive Pools

The soil, with an estimated 2500 Pg of C, is the biggest active terrestrial C reservoir, containing 620 Pg of C in the terrestrial biota and detritus and 780 Pg of C in the atmosphere (Lal 2010). In connection with the easy movement of carbon between the pools referred to as active pools, it is estimated that approximately 90,000,000 Pg of carbon is present in the earth's crust geological formations out of which 38,000 Pg of carbon is present in the ocean as dissolved carbonates, 10,000 Pg of carbon is sequestered as gas hydrates, and 4000 Pg of carbon as fossil fuels (Rustad et al. 2000) which are collectively referred as inactive pools because a majority of the carbon in these pools have been locked up over long periods of geologic time and are not readily exchanged.

### 5.1.5 Soils and the Carbon Sequestration

Naturally, soils can sequester C through the soil-plant system by transferring the dead tissues to the soil during the process of photosynthesis (Lal et al. 1998). Carbon is spontaneously exhaled from soils as $CO_2$ and $CH_4$ gases. The C balance in managed soils is heavily influenced by human actions. Studies indicated that the practice of no-tillage favors a higher accumulation of C in the top 15–20 cm of the soil (Bakker et al. 2007). Low $CO_2$ emission and greater C sequestration of soils can be obtained by following soil management techniques like no-tillage when compared to intensive tillage (Post et al. 2004). Other management adjustments, such as the use of cover crops, crop rotation rather than monocropping, reducing or eliminating fallow times (Álvaro-Fuentes and Paustian 2011), and reverting land to native forest or grassland (Post and Kwon 2000), might contribute to soil C sequestration. C sequestration is typically rapid at first and then slows down over time (Silver et al. 2000); following management adjustments, most agricultural soils will only absorb C for 50–150 years before reaching C saturation (Mosier 1998).

$CO_2$ emissions dominate in well-aerated soils, whereas $CH_4$ production is linked to anaerobic conditions. The balance between C added and released from the soil will determine the increase or decrease of total C levels in the soil (Rist et al. 2013). When carbon is removed from the atmosphere, it causes a rise in carbon levels in soil and vice versa. To understand the significance of this chapter, it is necessary, to begin with, a definition of land. The land is defined as "the terrestrial portion of the biosphere that comprises the natural resources (soil, near-surface air, vegetation, other biotas, and water), ecological processes, topography, human settlements, and infrastructure that operate within the system." Land degradation is a long-drawn deterioration of biological production, ecological integrity, and human worth caused by direct or indirect human-induced processes such as anthropogenic climate change. Forest abasement refers to the deterioration of forest land. Land degradation is the process that affects the soil directly by degrading the soil.

## 5.2 Land Degradation Vis-à-Vis Agriculture

Land degradation has long-term effects on biological production and ecological integrity, resulting in a loss of biological productivity and ecological integrity. Direct human pilots of land degradation include changes in the land-use system, and poor land management practices in agriculture are the most prominent industry generating degradation. Loss of soil due to conventional tillage is more than two orders of magnitude faster than soil formation. Climate change accelerates and intensifies some existing land degradation processes while also introducing novel degradation patterns. Human-induced global warming has led to increased frequency, severity in precipitation rate, as well as increased heat stress. Coastal erosion has been worsened in some regions which lead to the rise of sea levels. Beyond today's levels of global warming, ongoing land degradation processes will be exacerbated by increased floods, drought frequency and severity, stronger cyclones, and sea level rise, with the effects being adjusted by land management.

It is estimated that 1.5 billion people around the world rely on degraded lands for their livelihood. People who depend on natural resources for food security and income for their survival are more at risk of land degradation and climate change in degraded areas. Land degradation and climate change function as a threat to precarious livelihoods, making them more vulnerable to extreme weather events, resulting in poverty and food insecurity and, under some circumstances, leading to migration, conflict, and loss of cultural heritage. Change in the climate may also impose its effect on vegetative cover and its distribution which increases the danger of land degradation.

Land degradation is a phenomenon of climate change that slows down the process of carbon absorption. It is reported that before the cultivation of cropland, soils have lost 20–60% of their organic carbon content and the soils being used in conventional agriculture will continue to emit GHGs. Deforestation, rising wildfires, degradation of peat soils, and permafrost thawing are the land degradation processes that contribute the most to climate change by releasing GHGs and reducing land carbon sinks. Conversion of primary forests into managed forests, illegal logging, and unsustainable forest management are the likely causes for the emission of GHG which have further physical implications on local climatic conditions.

## 5.3 Biomass Production Threat to Food Security and Land Degradation

Excess application of fertilizers, irrigation, and monocropping of high-energy plantings can increase biomass production, and at the same time, they may lead to local land degradation. Land degradation is exacerbated by poorly implemented land management practices (e.g., salinization from irrigation). Energy crop impacts can be mitigated by strategically integrating them with agricultural and forestry systems.

Preventing deforestation, expanding the carbon sinks, and contributing toward GHG emission reduction goals can contribute to sustainable forest management. Sustainable forest management can deliver socio-economic benefits for fiber, timber, and biomass to meet society’s expanding demands. Furthermore, it can improve carbon stores and biodiversity in damaged forest areas. Carbon storage in long-lived wood products, as well as emission reductions by using wood products to replace emissions-intensive commodities, ultimately helps to meet mitigation goals.

## 5.4 Sustainable Land Management (SLM) and Sustainable Forest Management (SFM)

“The stewardship use of land resources such as soils, water, animals and plants to fulfill human requirements while also guaranteeing these resources’ long-term productive potential and environmental functions” is regarded as SLM. Use of forests and forest lands in a way and at a rate that maintains their biodiversity, productivity, regeneration capacity, vitality, and potential to fulfill relevant ecological, economic, and social functions now and in the future at local, national, and global levels, while causing no harm to other ecosystems (Mackey et al. 2015).

Climate change interacts with land management to determine whether a system is viable or degraded. Climate change has the potential to worsen several degradation processes while also introducing new biome shifts. Land management activities are chosen to minimize the impacts of climate change and adapt to climate change to avoid, lessen, or reverse the damage. Longer growing seasons, for example, can contribute to better forest productivity (Henttonen et al. 2017), but warming alone may not be enough in areas where water supply is a major constraint (Hember et al. 2017).

The intensity of the land-use system and the impact of climate change will determine the land carbon stocks and their potential role as carbon sinks. Degradation of agricultural lands results in lower soil organic carbon stocks due to continuous tillage practices having a negative impact on land productivity and carbon sinks. The younger forests have a faster growth rate and hence contribute more carbon sinks than older forests (Poorter et al. 2016).

## 5.5 The Human Facet of Land Degradation and Forest Degradation

Degradation of land and forest is frequently oriented toward biophysical characteristics which are contributed by the factors like erosion of soil, depletion of nutrients, and physical manifestations which results in lower productivity. When it comes to deterioration, policymakers and scientists have frequently overlooked or ignored land users' opinions and knowledge of land conditions (Anderson et al. 2011). Land usage and management are strongly gendered, and this is likely to continue for the foreseeable future (Kristjanson et al. 2017). Even though they perform many of the land management responsibilities, women have less access and influence over land than males. Land rights vary by location and are influenced by political, economic, and legal factors (Montanarella et al. 2018) which indicates that there is no one-size-fits-all ideal solution. Land degradation is caused by a complicated chain of events, making it difficult to distinguish between direct and indirect sources. The complementary effects of these processes which exist between each other add layer of complexity to climate change.

## 5.6 Factors Affecting Land Degradation

Land degradation mainly includes the processes of land degradation (direct drivers) and drivers of land degradation (indirect drivers).

### 5.6.1 Processes of Land Degradation

Land degradation is caused by a complex combination of physical, chemical, biological, and human activities (Johnson and Lewis 2007). The functional and structural traits of the ecosystem (biological productivity and ecological integrity) and benefits of people received from the land (human value) will suffer by the process of land degradation which will be triggered by a single furrow (e.g., water erosion under cultivation) to the landscape level (e.g., salinization due to rising groundwater levels under irrigation). The pressure created due to land degradation is directed to create a negative impact on land-use systems that is on soil, water, and biota. The degradation of one factor has a great impact on the remaining factors due to the series of interaction effects.

Depletion of organic matter in the pool is the first-order process that is triggered by the rising global temperatures (Crowther et al. 2016), and it also continues to bring changes or variations in precipitation patterns or intensities. Under natural circumstances, it is very difficult to categorize the numerous channels which created pressure on land degradation through climate change which is known for its complexity.

The popular method of developing arable land is by converting the freshwater wetlands into agricultural land known for a long time ago. Freshwater wetlands, despite their tiny aerial extent of roughly 1% of the earth's surface (Dixon et al. 2016), provide a wide range of ecological services, including groundwater replenishment, flood protection, and nutrient retention, as well as being biodiversity hotspots (Reis et al. 2017). Wetland loss has been estimated to be over 55% globally since 1900 (Davidson 2014) and 35% since 1970 (Darrah et al. 2019), which poses an issue for climate change adaptation in many settings.

### 5.6.2 Types of Land Degradation Processes

The process of land degradation affects soil, water, and the biotics and the interaction between them. Among the land degradation processes, it is the soil that is having prominent attention. Water and wind erosion followed agriculture from its inception, and it will continue to be dominant. Degradation due to the process of erosion is not only limited to the loss of soils in detachment areas but also has a great impact on transportation and deposition zones.

Coastal erosion is a unique erosional mechanism that is linked to climate change in recent research times, while human interventions such as shrimp farm expansion and economic activities causing land subsidence (Allison et al. 2016) are the most prominent human drivers causing degradation in coastal areas (Mentaschi et al. 2008).

The processes of chemical degradation of soils may be identified by the alterations and depletion of nutrients caused by an imbalance in nutrient extraction of harvested products and fertilization to more sophisticated ones like acidification and increased metal toxicity. Excess applications of nitrogenous fertilizer are acting as drivers for the process of acidification in croplands by the loss of cations like calcium, potassium, and magnesium through exports in harvested biomass (Guo et al. 2010). The depletion of the organic matter pool in agricultural soils due to increased respiration rates because of the continuous tillage practices and the loss of belowground plant biomass inputs is one of the most important chemical degradation processes of soils in the context of climate change. The direct impacts of warming have also reduced soil organic matter pools, not just in farmed land but also in natural vegetation. Changes in the hydrological system can be caused by land degradation processes, which are relevant to climate change. Soil salinization is observed due to rising water tables, which push salts to the surface in dry to subhumid climates (Schofield and Kirkby 2003). All types of erosions, declining soil organic matter, salinization and sodification of soils, water logging of dry ecosystems and drying of wet ecosystems biological invasions, pest outbreaks, and biological soil crust destruction are the factors posed to cause land degradation in face of climate change.

### 5.6.3 Drivers of Land Degradation

The factors that contribute to land degradation and improvement are numerous and interact in a variety of ways. It's crucial to remember that both natural and human causes can contribute to degeneration or improvement (Kiage 2013). Land degradation is caused by a wide range of processes ranging from relatively brief and intense events, such as single 10-minute rainstorms eroding topsoil or causing a gully or landslide (Coppus and Imeson 2002) to century-scale sluggish nutrient depletion or soil particle loss. Rather than focusing on absolute temporal fluctuations, the drivers of land degradation might be evaluated in terms of probable recovery rates. Unfortunately, soil formation rates are difficult to monitor because of the sluggish rate; this is impracticable to perform in a spatially detailed manner. Gradual increases in temperature, precipitation, and wind as well as changes in the distribution and intensity of extreme events are the climate change-related drivers of land degradation (Lin and Huybers 2012). These drivers worth noting can have two effects: land improvement and land deterioration. Even if the net effect is modified by other factors like nitrogen availability (Terrer et al. 2016) and water availability, increasing $CO_2$ levels in the atmosphere is a driver of land improvement. Some of the indirect drivers include demographic shifts, technological advancements, changes in consumption habits and nutritional choices, political and economic shifts, and social shifts (Mirzabaev et al. 2016). It's critical to emphasize that there are no straightforward links between underlying forces and land degradation like poverty and high population density leading to land degradation (Lambin et al. 2001). Land degradation drivers, on the other hand, must be investigated in the view of spatial, temporal, economic, environmental, and cultural factors (Warren and Degrad Dev 2002).

Several climate variables, such as temperature, precipitation, wind, and seasonality, are intricately connected to land degradation. This strongly indicates that climate change and land degradation are related in a variety of ways. Rather than a set of cause-effect correlations, the linkages are better represented as a web of causality. It's impossible to draw a clear line between procedures and drives. Drought and fires are described as land degradation causes. For example, if recurrent fires deplete seed sources, they might impair forest ecosystem regeneration and succession. Land degradation responses follow the logic of the LDN concept, i.e., avoiding, reducing, and reversing land degradation (Orr et al. 2017). Climate and climate variability are frequently intrinsic elements in land degradation. The role of climate change, on the other hand, is less well defined. Climate change is viewed as either a process or a driver of land degradation, or both, depending on the conceptual framework employed.

## 5.7 Attribution of Climate Change Concerning Land Degradation

The question here is whether or not land degradation may be linked to climate change and vice versa. Multiple climatic factors (rainfall, temperature, and wind), abiotic ecological factors (soil characteristics and topography), type of land use (farming, various types of forestry, or protected areas), and land management practices (tilling, crop rotation, and logging/thinning) all contribute to land degradation. As a result, linking land degradation to climate change is extremely difficult. Because land degradation is so closely linked to land management, it's feasible that climate change will prompt improvements in land management, either by reducing or reversing land degradation, a process known as a transformative adaptation (Kates et al. 2012). There isn't a lot of research linking land degradation to climate change directly, but there is a lot of evidence linking climate change to land degradation as a threat multiplier. However, both conceptually and empirically, it is possible to deduce climate change implications on land degradation in some circumstances.

Land degradation in form of soil carbon loss has been going on for at least 12,000 years but has accelerated in the last 200 years (Sanderman et al. 2017). Before the introduction of modern fertilizer sources, farmers were required to maintain and improve soil fertility by preventing runoff and erosion and managing nutrients through vegetative residues and manure. Because nutrients and water are provided externally in modern agriculture, preserving biological productivity and ecological integrity of farmland is no longer as important as it was in pre-modern agriculture. Sustainable land management is a unified framework for tackling land degradation that can be characterized as the care and use of land resources like soils, water, animals, and plants to fulfill changing human requirements while also guaranteeing these resources' long-term productive potential and environmental functions. It's a holistic approach that includes technologies as well as the social, economic, and political contexts that make them possible (Nkonya et al. 2011). It's critical to emphasize that both scientific and local/traditional knowledge inform farming practices.

## 5.8 Localized Efforts to Combat Land Deterioration

Soil and water conservation should be considered as the primary focus of concrete measures on the ground to combat land deterioration. In the context of changing climate, the actions useful for tackling land degradation are sometimes framed under ecosystem-based adaptation (Scarano 2017) or nature-based solutions (Nesshöver et al. 2017). For the successful implementation of actual activities, site-specific biophysical, social circumstances, and local and indigenous knowledge are very much essential. Agronomic measures like managing vegetation cover, methods of tillage and nutrient supply, and mechanical methods that result in long-term changes to the landscape are considered the most common responses to land degradation (Morgan 2005). The actions can be implemented to improve land quality while also increasing carbon sequestration which aids in climate change mitigation, some measures such as agroforestry which involves planting fruit trees to support food security in the face of climate change impacts (Reed and Stringer 2016) or the application of compost or biochar which improves soil water-holding capacity and thus increases drought resilience which provides adoptive methods and gives co-benefits.

## 5.9 Predictions of Land Deterioration Due to Climate Change

The significant effects of land degradation due to the changing climate include rising temperatures, altering rainfall patterns, and high-intensity rainfall. These changes will result in changed rates of erosion and the processes that drive an increase and decrease in the erosion of soil in various combinations. In terms of attribution, it's worth noting that precipitation estimates are, on average, more unpredictable than temperature change projections (Murphy et al. 2004). Precipitation includes more complex local dynamics than temperature. Therefore, predictions for precipitation are typically less reliable than those for temperature (Pendergrass and Knutti 2018).

Land degradation is influenced by the distribution of wet and dry periods, yet there are still uncertainties because forecasting relies on climate models with lower resolution (Kendon et al. 2014). Changes in rainfall timing may have a substantial impact on soil erosion processes by changing how wet and dry soils are (Lado et al. 2004). Changes in evapotranspiration and evaporation alter soil moisture content, which can affect water partitioning into the surface and subsurface runoff (Li and Fang 2016). The amount of rain that falls at different parts of the day can have a big impact on erosion (Stocking et al. 2001). Erosion due to the wind is a significant issue in cultivated areas, not just in dry lands. In recent decades, the wind speeds near the surface across different places have been reduced. Climate change, which includes rising $CO_2$ levels in the atmosphere, has an impact on vegetation structure and function, eventually leading to land degradation. It's still a work in progress to figure out how vegetation reacts to changes.

The changing climate is having both direct and indirect impacts on land degradation, and land degradation will feed into climate systems to some extent. The interaction between the climate and land is both temporal and spatial resulting in direct repercussions. Increased rainfall intensity, for example, exacerbates soil erosion, and extended droughts lower soil vegetation cover, leading to more soil erosion and nutrient loss. The impacts of land degradation and changing climate that are distributed temporally and spatially are referred to as indirect impacts. For example, decreased agricultural productivity brought on by climate change may encourage agricultural intensification elsewhere, which might feed back into the climate system and accelerate current climate change.

Although many processes of land degradation are accelerated by climate change, it is challenging to anticipate future land degradation since land management methods greatly influence the state of the land. Models of land degradation and climate change scenarios can be used to assess the kind and quantity of land management that will be needed to prevent, minimize, and alter land degradation.

### 5.9.1 Land Degradation's Direct Effects

There are two levels of uncertainty to consider when analyzing the risks of future climate change that has resulted in land degradation. Changes in the degrading agent, such as precipitation erosive power, heat stress from rising temperature extremes (Hüve et al. 2011), water stress from droughts, and high surface wind speed, all occur at the first level, where uncertainties are rather low.

There are two levels of uncertainties to be considered when analyzing the risks of future climate change that has resulted in land degradation. Level one includes the changes in the erosive power of the rainfall, rising and declining temperatures, drought conditions, and increased wind speeds near the surface where the risks are rather minimal, whereas the second level of uncertainty, which has substantially bigger uncertainties, is related to the biological changes aboveground as well as belowground as a consequence of changing precipitation, temperature, and rising $CO_2$ levels. Mullan et al. (2012) both pointed out the importance of vegetation cover in preventing erosion.

Changes in precipitation patterns both in space and time as well as exacerbation of floods and droughts will enhance the likelihood and consequences of degradation of the land. In some regions, where there is a change in vegetation cover leads to the reduction in native crop species ultimately rising the danger of land degradation. Extreme rainfall events cause landslides, which are a type of land degradation. Coastal erosion is more common as sea levels rise around the planet. In cyclone-prone locations, the combination of rising sea levels, more violent cyclones (Walsh et al. 2016), and land subsidence (Yang et al. 2019) will create a serious threat to people and livelihoods.

### 5.9.2 Land Degradation's Indirect Effects

Because of the various confounding factors, the indirect effects are difficult to assess. Land-use change has several reasons including physical, biological, and socio-economic factors (Lambin and Meyfroidt 2011). The degradation of agricultural land is one of the causes of land-use change, which can lead to a negative impact by converting the natural land for agricultural purposes for maintaining agricultural production. Intensified agricultural land management may result in loss of soil's potential, which has a negative influence on ecosystem services provided by soils such as keeping the water quality and carbon sequestration (Smith 2016). Cropping-induced soil degradation is of utmost importance in tropical climates leading to a reduction in land's productive potential, threatening the food security at the regional level, and forcing the transfer of forest land to agriculture (Drescher et al. 2016).

Climate change will worsen these negative cycles unless SLM strategies are implemented.

Climate change's effects on agricultural productivity will have an impact on land-use intensity, raising the danger of further land degradation. Localized impacts (land use in the same region) and teleconnections (land-use changes that are different in space and time) will both exist (Wicke et al. 2012). If global temperatures rise by more than 3 °C, all crops will experience lower yields. This combined with a doubling of demand by 2050 (Tilman et al. 2011) and increased competition for land due to industrial expansions and emissions will put a strain on agricultural lands and food security.

### 5.9.3 Effects of Land Degradation Brought on by Climate Change on Food Security

Land degradation, climatic conditions, and food security all revolve around how and where we grow food in comparison to where and when we need to eat it, because rain-fed food production is limited to more than 75% of the total land surface (except Antarctica) (Fischer et al. 2009) (Table 5.1).

## 5.10 Land Degradation Neutrality (LDN)

The UNCCD was the first to use LDN. LDN is defined as "a condition in which the quantity and quality of land resources needed for upkeeping the ecosystem functions and services and promote food security stay steady or increase throughout time and across scales and ecosystems" (Cowie et al. 2018). To achieve LDN, efforts must be made to avert additional net losses of land-based natural capital in comparison to a baseline condition. LDN supports a two-pronged approach involving SLM to mitigate the negative impacts of land degradation, as well as initiatives in restoring the land and rehabilitating it to sustain or improve land-based natural capital and ecosystem services. As a result, achieving LDN necessitates a unified approach to landscape management which aims at optimizing the land use to achieve numerous goals like food security, wellness of human beings, and ecosystem health.

## 5.11 Potential Options in Achieving LDN

### 5.11.1 Agricultural and Soil Management Techniques

SLM aims to rebuild soil carbon which is especially crucial in the light of climate change (Rumpel et al. 2018). Frequent disturbance of agricultural soils through tillage and harvesting as well as a transition from deep-rooted perennial plants to shallow-rooted annual plants might be the reasons for the loss of 20–60% of the soil carbon by the agricultural soils they retain under the natural ecosystem conditions

**Table 5.1** Desertification and land degradation as outraged by human and climate interactions

| Issue | Impact on climate change (emissions) | Human-induced factors | Climatic factors | Potential land management options |
|---|---|---|---|---|
| Erosion of agricultural soils | $CO_2$, $N_2O$ | Practices like agriculture expansion | Warming trend<br>Drying trend<br>Intense rainfall<br>Rainfall pattern shifts | Increased organic matter in the soil, no-till methods, perennial crops, and agroforestry |
| Deforestation | $CO_2$ | Forest clearing<br>Expansion of agriculture | | Forest protection, sustainable forest management, and dietary change |
| Forest degradation | $CO_2$ | Forest clearing | | Forest protection, sustainable forest management |
| Overgrazing | $CO_2$, $CH_4$ increasing albedo | Grazing pressure | Warming trend<br>Drying trend | Controlled grazing, rangeland management |
| Firewood and charcoal production | $CO_2$, $CH_4$ increasing albedo | Wood fuel | | Clean cooking benefitting the health of women and children |
| Fire intensity and frequency | $CO_2$, $CH_4$, $N_2O$, aerosols, increasing albedo | | Warming trend<br>Extreme temperature<br>Drying trend | Fuel management, fire management |
| Tropical peat soils degradation | $CO_2$, $CH_4$ | Agriculture practice<br>Expansion of agriculture | Drying trend | Peatland restoration of peatlands, control of erosion, regulating the use of peat soils |
| Coastal erosion | $CO_2$, $CH_4$ | | Intensifying cyclones<br>Sea level rise<br>Extreme rainfall | Conservation of mangrove, long-term land-use planning system |
| Wind erosion (sand and dust storms) | Aerosols | Agriculture expansion<br>Grazing pressure<br>Wood fuel | Drying trend<br>Shifting rains | Vegetation management, afforestation, windbreaks |

(Crews and Rumsey 2017). Practices that enhance the organic matter additions to the soil or minimize SOM degradation help to build soil carbon. By boosting the organic additions of leaf litter and roots into the soil, agronomic activities can drastically affect the carbon balance. During the winter, green manure crops replace the fallow fields and are finally ploughed before seeding the next primary crop including residue retention; using plants native to that area, intercropping, and crop rotations can build the soil organic carbon (Henry et al. 2018). Cover crops and catch crops produced in the fallow periods can boost soil carbon store by 0.22 to 0.4 t C $ha^{-1}$ $year^{-1}$. Conservation tillage practices like reduced tillage or no-tillage can be essential methods for controlling wind and water erosion as well as the fertility status of the soil. However, there is no compelling information on carbon sequestration by adopting no-till agriculture. Only sampling the top 30 cm of soil can lead to skewed results, implying that no-till soils have more carbon content compared to regularly tilled fields. Soil carbon content can be increased by switching from annual to perennial crops (Sainju et al. 2017). A perennial grain crop (intermediate wheatgrass) has a net carbon drop of roughly 13.5 t $CO_2$ $ha^{-1}$ $year^{-1}$ on average over 4 years (Oliver et al. 2012). The amount of carbon that can be stored and over what period by switching from annual to perennial crops is determined by the degree of carbon depletion in the soil as well as other biophysical parameters in that area. To meet soil chemical restrictions, integrated soil fertility management employs the use of chemical as well as organic supplements, green manure crops for nitrogen fixation, and chemical amendments for the amelioration of the problematic soils. In pasture systems, grazing pressure controls fertilization, and various plants such as legumes and perennial grasses help to prevent erosion and increase the carbon content of the soil (Conant et al. 2017).

### 5.11.2 Mechanically Conserving Soil and Water

Terracing is an ancient practice but is still used as a soil protection strategy in steep and mountainous terrain (Preti and Romano 2014) in climatic zones ranging from desert to wet tropics (Balbo 2017). Terraces create level areas by lowering the slope gradient of hillsides. Deep, loose soils that allow more water to percolate through them diminish erosion and, as a result, sediment transfer. They also restrict hydrological connection, resulting in less hillside runoff.

### 5.11.3 Agroforestry

Agroforestry is a land-use system in which trees and shrubs are grown in conjunction with crops or pastures in a spatial arrangement and in which the trees and agriculture components of the system interact ecologically and economically (Young 1995). When compared to monoculture crop systems, there is considerable scientific consensus that agroforestry systems can render improved ecosystem services. Agroforestry can help to achieve sustainable intensification by permitting better productivity output on the same unit of land without the requirement for moving present agriculture patterns to sustain crop yields (Nath et al. 2016). Agroforestry for perennial crops such as coffee and cocoa is fast-gaining popularity as a means of achieving more sustainable agriculture practice while also providing co-benefits for climate change adaptation and mitigation (Kroeger et al. 2017). Co-benefits of agroforestry in cocoa production include increased carbon sequestration in soils and biomass, improved water and fertilizer use efficiency, and the creation of a favorable microclimate for crop productivity (Sonwa et al. 2017). Importantly, the use of agroforestry to maintain soil fertility has the potential to reduce deforestation caused by shifting agriculture (of cocoa). Positive interactions within these systems, on the other hand, can be ecological and/or species-specific, and co-benefits like increased resilience to catastrophic climate events or increased soil fertility aren't always found (Blaser et al. 2017). These disparate results (Sonwa et al. 2014) show the importance of field-scale research initiatives in guiding agroforestry system design, species selection, and management strategies.

### 5.11.4 Local Farmers' Knowledge of Addressing Land Degradation

The interest in researching how indigenous and local knowledge affect land users' responses to degradation appears to be growing, involving farmers as experts in processes of knowledge co-production and co-innovation. Indeed, numerous studies have emphasized the necessity of including local communities in sustainable land and forest management.

### 5.11.5 Decreasing Deforestation, Improving Forest Quality, and Boosting Afforestation

Land-based natural climate solutions can be aided by improved forest stewardship, including decreased or prevented deforestation and forest degradation as well as increased carbon storage in forest ecosystems (Angelsen et al. 2018). The natural regeneration of second-growth forests enhances carbon sinks in the global carbon budget (Chazdon and Uriarte 2016). Transformational improvements were needed, from technical mitigation potentials (Miles et al. 2015) to actual emissions reductions from deforestation and forest degradation. The presence of already enacted policy changes and a scarcity of forest resources paired with an ineffective forestry framework and policies are two enabling circumstances that can help this transformation. Strong ownership and leadership, regulations and law enforcement, performance-based funding, and emissions from deforestation and forest degradation in developing nations can all work together to make REDD goals easier to achieve. Another mitigation action that enhances carbon sequestration is afforestation. However, given changing local albedo (short wave reflectivity) and changes in the turbulent energy, as well as rising night-time land surface temperatures, careful planning of tree planting locations is necessary to maximize possible climatic benefits (Peng et al. 2014). Maintaining and expanding forest areas, particularly native forests as opposed to monoculture and short-rotation plantations native forests rather than monoculture and short-rotation plantations, helps to maintain stable global forest carbon stocks (Lewis et al. 2019).

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# 6

# Establishing Linkages among Changes in Land Use, Vegetation, and Croplands to Arrest Soil Erosion and Desertification

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## Abstract

Land-use change (LUC) is considered as one of the main drivers of accelerated soil erosion and desertification. Changes in land use and land cover are mainly triggered by the interaction between demographic and socioeconomic changes as well as biophysical conditions, which further becomes one of the main driving forces on global and local environmental changes. The annual soil loss is estimated to be 35.9 Pg year$^{-1}$ globally and the major factor for such soil loss being cropland expansion. Such changes further have direct implications on carbon and nutrient cycling, productivity, and socioeconomic conditions. In India presently 49.3% of total area is under cropland. The expansion of cropland (0.08 million sq. km year$^{-1}$) with present agricultural practices will be

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responsible for 40% to 44% of predicted topsoil loss in India by 2100 (9.88% of land surface). This scenario can be prevented by adopting land conservation strategies and increasing overall forest cover. Land-cover changes, viz., cover cropping, agroforestry, and conservation agriculture, will help in combating soil erosion at field level, while understanding the linkages between land-use change, vegetation, and cropland is necessary for proper planning of sustainable strategies to arrest soil erosion and improve ecosystem services.

**Keywords**

Cropland · Desertification · Land cover · Land use · Soil erosion

## 6.1 Introduction

India is a developing country where agriculture seems to be the backbone of Indian economy. Land, water, and vegetation are crucial resources of India. India's participation in globalization made its transition toward steady economic growth and accelerated GDP. With the development of economy and reformulation of policy, there was change in traditional land use toward industries, mining, etc. Population growth led to migration and urbanization. Total cover under forest was decreased. In order to meet the food production of growing population, there was increasing in cropland area (Pal et al. 2021).

Land use is a crucial factor that influences not only agricultural productivity but also ecological equilibrium. These land-use and land-cover changes (LULC) had significant impact on environment and ecosystem. Ecological equilibrium is disrupted due to change in cropped area and other agricultural activities, human settlements, industrial built-up areas, and mining activities (Tripathi et al. 2019). Such changes also have its impacts on climate and soils as well as food security (Batunacun et al. 2018). Land degradation, soil erosion, and desertification are the results of increased pressure on resource by LULC.

In India presently 49.3% of total area is under cropland. The expansion of cropland (0.08 million sq. km year$^{-1}$) with present agricultural practices will be responsible for 40% to 44% of predicted topsoil loss in India by 2100 (9.88% of land surface) (Pal et al. 2021). To arrest soil erosion and optimize land management practices for better productivity and ecosystem service, it is necessary to have thorough knowledge of relationship between land use and land degradation.

With the advancement in remote sensing, GIS, and image-processing technologies, it gives us ample opportunities to examine the spatial and temporal changes in land use and land cover, which will give us knowledge of linkage between land use, land degradation, and soil erosion. We can also predict the future scenario of land degradation, soil erosion, and desertification if present management is continued. Establishing clear linkage gives ideas to policymakers, stakeholders, and farmers for alternate land management practices for arresting soil erosion and land degradation. This chapter deals with the impact of changes in land use, vegetation, and cropland on soil erosion and desertification and ways to establish relationship between land-use change and soil erosion for planning alternate land-use systems.

## 6.2 Land-Use Systems

Land use on broader view can be defined as the function for which the land is primarily utilized or simply the use of land by humans. There are different types of land uses based on its major purpose. The type of land use mainly depends on human habitat, population, and migrations. The major types of land use are, viz., residential, industrial, agricultural, mining, and recreational. The types of land use may be economical or cultural. In India, Directorate of Economics and Statistics, Ministry of Agriculture, and Government of India classified land use under different categories (Sridhar and Wan 2014) which are as follows:

- **Forest area:** Which mainly includes those lands under forest covers either by legal enactment or administered under forest governance. The areas of crops or grazing falling within the forest are also included in forest area.
- **Agricultural area:** The total area which is under agriculture and horticultural crops.
- **Nonagricultural uses:** The land areas which are mainly occupied for residential uses like buildings, roadways, railways, etc.
- **Barren and nonarable land:** The land area which cannot be brought under cultivation purposes like desert or mountains.
- **Permanent pastures:** Which include the land area utilized for grazing and pasture in villages.
- **Arable waste lands:** The type of lands which are cultivable but not taken up for cultivation for once or in last 5 years.
- **Fallow land and current fallow**: This includes all the land types which are under temporarily out of cultivation for some reasons.
- **Miscellaneous land:** The land under miscellaneous plants like casuarina trees, thatching grasses, bamboo bushes, and other groves for fuel, etc. which are not included under orchards.

Presently, major portion of land area is under agricultural use, viz., 60.4 percent of the total area, while the area under forest is about 24.3 percent (Sridhar and Wan 2014). The major focus of changes in land-use pattern mainly in agricultural and forestry affects the environment as well as economics of the country. Land-use trend is changing which changes in nature of economic activities and governmental policies. Such changes in land use have wide range of impact in environment, ecosystem, and biodiversity.

## 6.3 Land-Use and Land-Cover Changes (LULC)

Land-use change refers to the process by which natural landscape is transformed by human activities. Land-use changes are broadly broad into two categories, viz., conversion and modification. Conversion refers to the shift of one land cover to another, while modification is maintaining the land cover by changing the plant or tree species (Paul and Rashid 2017). The major form of land-use change in India is mainly conversion of land to agricultural management and urbanization.

### 6.3.1 Types of Land -Use Changes and their Major Drivers

There are different causes for changes in land use and vegetation, the major ones being population growth and developmental policies. But those are not only the sole causes of land-use changes. People's responses to economic opportunities and institutional factors also act as drivers of land-use change. The major land-use change and driving forces are discussed as follows.

#### 6.3.1.1 Deforestation

Deforestation is essentially the purposeful clearance of forest land. Deforestation is commonly linked to population growth and poverty, shifting cultivation of large forest area. While shifting cultivation is a driver of deforestation, it's not the sole driver; the main triggering mechanism is the national governmental policies and economic development. Migration of population is also a major reason for large scale deforestation (Lambin et al. 2001).

#### 6.3.1.2 Rangeland Modification

Rangelands are grasslands or pasture lands used by grazers or browsers. The modification in rangelands is mainly due to improper livestock management. Over grazing practice by traditional pastoralism is the main trigger for degradation of rangelands.

#### 6.3.1.3 Agricultural Intensification

Population growth leads to intensification of agriculture in unsustainable manner. Land scarcity triggers expansion of agricultural land area and also inappropriate use of agricultural inputs (Lambin et al. 2001). Market-oriented crop production leads to monocropping of high-value crops, and governmental policies toward agricultural market also drive into intensification of agriculture. Such unsustainable intensification leads to land degradation.

#### 6.3.1.4 Urbanization

Urbanization is often ignored in land-use change studies, yet it is the major form of land-use change. Migration of population toward cities leads to urbanization of croplands adjacent to cities. Migration and extension of peri-urban settlements are the major drivers leading to urbanization.

## 6.4 Impact of Land-Use Change on Land Degradation

Land-use and land-cover change (LUCC) has various impacts on natural habitat and environment. LUCC has impact on biodiversity, climate change, and soil erosion (Batunacun et al. 2018). These impacts also affect the food security and causes land degradation. Land degradation is defined as any loss of soil quality, productivity, species richness, livelihood, or in the provision of other ecosystem goods and services, ranging from slight decline to complete destruction or transition into different land uses (Batunacun et al. 2018). The disruption in the natural equilibrium due to LUCC produces effects on soil carbon stocks and soil properties, which on further intensifies to soil. All these factors finally attribute to the land degradation and desertification.

### 6.4.1 Impact of Changes in Land Use on Soil Erosion

Land-use and land-cover change has a major role on soil erosion processes. In India post-Green Revolution, high intense conventional agriculture and conversion of unconventional areas under cropping have impacted on soil erosion. Pal et al. 2021 tried to produce spatial distribution-wise soil erosion map of entire India. According to their study, the expansion of cropland in 2100 predicted year will be responsible for 40% to 44% of predicted soil erosion. The decline in forest area is also responsible for the predicted soil erosion.

The soil erosion rate increases with expansion of degraded forest area, urban settlement area, and declining forest. But such erosion rate decreases with cropped areas which are previously barren, either single-cropped or double-cropped areas. It is found that barren land and degraded forest land had higher susceptibility to soil erosion as compared to forest and croplands (Bhattacharya et al. 2021).

Impact of land-cover changes on soil erosion also depends on another important factor of soil erosion which is rainfall. It is found that cropping in highly susceptible areas of water erosion is found to significantly reduce the erosion rate and impact. The rainfall erosivity will increase if there is a poor management of urban, barren, cropland, and grassland, which soil water conservation structures and forest areas will reduce the erosivity due to rainfall (Maurya et al. 2021).

Munoth and Goyal (2020) in their study on impact of land-use and land-cover change on runoff and sediment yield of Upper Tapi River Sub-basin, India, they found that it is found that from the data collected over five decades, the area under is increased by 18%, whereas forest land and rangeland are decreased by 7% and 10%, respectively. This change resulted in 36% increased surface runoff and 22% increase in sediment yield. The changes in land use also impacted on ecological balance of river as well as forest habitat.

In areas of high rainfall zone of northeastern India, land under agriculture and wastelands are more prone to soil erosion that land under *Jhum* cultivation and forests. The areas under agriculture had less soil organic carbon (SOC), lesser permeability, and higher erosivity index compared to areas under other land-use system (Olaniya et al. 2020).

### 6.4.2 Impact of Changes in Land Use on Land Degradation and Desertification

Land degradation and desertification mostly depend on how the land is utilized. Lands utilized for economic purposes like mining poses huge problem through land degradation. Manendragarh coal mining area located in northern Chhattisgarh, Central India, has impacted in loss of 14.5% of forest area, 12.9% of agricultural area, and 2.5% of areas under water bodies. The intense mining activities have resulted in deterioration of soil health, where the organic C, pH, and soil depth were considerably decreased in mined sites and degraded lands compared to agricultural and forest areas (Pandey et al. 2022).

Land-use changes directly affect erosion potential and rate. Where land-use managers, which include farmers and herders, do not make efforts to replace or replenish soil as it is used, erosive processes can be particularly severe and result in accelerated erosion. Following erosion, sedimentation is the deposition of detached soil particles in new territorial, aquatic, or oceanic ecosystems. This affects the ecosystem both land and aquatic. Following erosion, sedimentation is the deposition of detached soil particles in new territorial, aquatic, or oceanic ecosystems. Changes in land use also aggravate already existing soil problems, viz., problems due to soil salinity, acidity, or heavy metal pollution (Hossain et al. 2020).

Intensive agricultural practices will also result in land degradation. Urbanization coupled with intensive agriculture will have negative pressure on environment as well as land. Such urbanization has resulted in loss of forest habitat and reduction in areas under cropland and forest of Punjab. Inappropriate agricultural activities have reduced the soil fertility and increased erosion and soil salinity. Subsequently, consequences of land degradation may lead to vegetation loss, soil degradation, and pollution of soil, water, and air in Punjab (Ahmad and Pandey 2018).

Desertification is also one of the primary environmental problems that negatively affect agricultural production leading to poverty, hunger, and economic instability in a country like India. Desertification is a widespread concern mainly in the western part of India. But it also has spread over to the southern part of the country. 33.8% of total land area is critically under desertification. Vegetation and land use play an important role in desertification. Bare land and cropland under rainfed area increase desertification in regions of Rajasthan and west part of India, while land under natural cover and forest is less prone to desertification. While the semiarid regions of South India face land degradation mostly through water-driven soil erosion caused by the lack of vegetation cover, salinization, wind erosion, and anthropogenic activities (Rajbanshi and Das 2021).

## 6.5 Impact of Changes in Vegetation on Soil Erosion

Vegetation controls soil erosion by means of its canopy, roots, and litter components, whereas, erosion also influences vegetation in terms of the composition, structure, and growth pattern of the plant community. Loss of vegetative cover may lead to the formation of soil seals (due to raindrop effect, mostly found in silty soils) that increase runoff and erosion during the early stages of seal development.

Soil erosion is affected by many factors, like climate, topography, vegetation cover, root systems, soil properties, and land management practices (Fu et al. 2010). It is usually quantified by the revised universal soil loss equation (RUSLE) (Renard et al. 1994). In comparison with other factors in RUSLE, vegetation cover is the most complex and unstable factor that influences soil erosion vulnerability, and this effect is enhanced with intensive human activities (Ochoa et al. 2016).

Vegetation promotes aggregation of soil microstructures that helps to mitigate the impact of erosive-powered precipitation. Living plant roots modify both mechanical and hydrological characteristics of the soil matrix and contribute to soil retention (Vannoppen et al. 2015). The change of vegetation cover is commonly detected by NDVI (normalized difference vegetation index), which is a comprehensive indicator to reflect the growth of plants, and it is directly linked to aboveground biomass. The aboveground biomass is closely related to the belowground biomass, which determines the root's ability in reducing soil erosion.

In many studies it has been observed that deforestation and intensive land cultivation are conducive for surface runoff and soil erosion. Intensity of runoff and soil erosion was found to depend mostly on the type of vegetative cover rather than the percent of vegetative cover.

Forests and natural vegetation dominated by *S. spinosum* decrease the risk of runoff and soil erosion, but the removal of this kind of vegetation and forest trees as a means to improve rangeland productivity conducive for runoff and sediment fluxes if not accompanied by careful grazing management. In addition, interchangeably using arid and semiarid lands as rangeland and for cultivation may have significant negative impacts on the production potential of these lands (Mohammad and Adam 2010).

### 6.5.1 Mechanism of Vegetation Effects on Soil Erosion

The mechanism of plants in controlling soil erosion can be summarized into three aspects. First, plants reduce the energy of raindrops with their canopy before it hits the soil, thus reducing the soil's ability to erode. Second, during the process of soil erosion, plant root holds the soil in position and prevents it from being swept or blown away. Roots hold the soil in place and redesign the rhizosphere to alter the three-dimensional physical architecture and water dynamics as a physical barrier (Bashir et al. 2018); moreover, high root density can protect soil detachment and increase infiltration, thus reducing soil loss. Third, during the process of soil deposition and redistribution, the plants slow down water as it flows over the land and reduce runoff by facilitating more infiltration of water into the ground.

In the community level, plant type, plant diversity, the vegetation structure, and the distribution pattern also affect the processes of runoff, soil erosion, and nutrient export. Liu et al. (2020) found the main vegetation types used in ecological restorations have different behaviors in reducing runoff and sediment yield, for example, grassland showed a higher performance in maintaining runoff yield and reducing sediment delivery compared to forestland and scrubland. Plant diversity can affect soil erosion and runoff by changing the pattern of vertical vegetation (Gómez et al. 2018), enhancing the light use efficiency of aboveground vegetation cover (Onoda et al. 2014) and increasing the diversity of the litter layer and root density (Liu et al. 2018b). The effects of the vegetation structure on rainfall include the aboveground layer, surface litter layer, and belowground root layer. The aboveground vegetation layer redistributes rainfall into canopy interception, stemflow, and throughfall, thereby the impact of rainfall reduces and thus controls soil erosion (Allen et al. 2014). Moreover, the litter layer can intercept rainfall, increase infiltration, decelerate surface runoff, and therefore reduce soil loss (Liu et al. 2018a).

In the landscape level, the spatial distribution of vegetation can greatly affect runoff and sediment yields (Wei et al. 2015). A change in vegetation will change the landscape connectivity and fragmentation level and will thus affect the surface runoff and sediment delivery (Fryirs 2013). Sparse vegetation increases runoff and sediment yield (Bautista et al. 2007). The relationship between vegetation cover and soil loss is also scale dependent, for example, at the patch or landscape level, we should pay more attention to the vegetation structure and plant diversity; at the catchment or regional scale, we should focus on the changes in vegetation cover.

## 6.6 Impact of Changes on Vegetation Due to Land Degradation and Desertification

The occurrence of desertification causes in changes in vegetation composition, pattern, and structure. The physical reservoir of carbon held in soil aggregates could be destroyed by soil erosion (Deng et al. 2018), resulting in a decrease in effective root depth, nutrient availability, and water-holding capacity in the root zone (Du et al. 2019). Soil erosion removes considerable quantities of topsoil, which will greatly influence soil nutrient stocks and soil pH and will impact soil nutrient redistribution and global biochemistry (Quinton et al. 2010). Desertification promotes changes in the vegetation pattern, e.g., shrub species replace herbaceous species in vegetation composition. The decrease in vegetation coverage and productivity would inevitably cause the loss of soil organic C and N with increasing desertification. Grassland desertification induces the release of greenhouse gases thereby loss of C and N from the soil into the atmosphere (Duan et al. 2001).

## 6.7 Impact of Changes in Cropland on Soil Erosion

Healthy soil is the fundamental asset that fulfills human and animal needs by providing food, fiber, fodder, etc. Soil is the base for primary ecosystem services and an important part of an ecosystem. A major threat to land, ocean, lakes, river, and ponds is soil degradation through erosion. In the twenty-first century, the main reason for an increase in soil erosion is land-use change (changes in cropland, grassland, and forest) and anthropogenic activity (agriculture, soil management, fire, grazing, and urbanization). Intensive cropland cultivation is the key driver of soil erosion, while crop management practices can reduce the erosion from croplands such as the use of cover crops and leguminous crops. According to changes in land use, soil erosion rates decrease from croplands to grassland and forests. Borrelli et al. (2020) estimated and reported that annual crops are accountable for 41% of total forecasted soil erosion in croplands. Moreover, agricultural lands including annual crops, pasture, and permanent crops are accountable for 54% of total soil erosion which is equal to 23.4 + 5.3 − 4.1 Pg yr. − 1 (Borrelli et al. 2020). At the global level, soil erosion by heavy irrigation or rainfall has increased at the rate of 2%; this is mainly driven by the increase in annual crops land at 2.1 million $km^2$. In general, cereal crops such as maize, cotton jawar, bajra, etc. are the key drivers of soil erosion, while legume crops such as soybean, matki, dolichos, and groundnut control the erosion.

Several factors are responsible for soil erosion such as changes in land use and cropland, agriculture practices, climate, soil properties, topography, and moisture availability. In dryland agriculture, two factors, i.e., soil moisture and vegetation cover, are the major drivers for accelerating soil erosion. Vegetation/crop cover protects the soil erosion by providing shelter from the erosive action of rainfall or irrigation and wind (Raupach 1992). Cropland surface covering by using biological or physical material also protects the soil erosion by rainfall or irrigation and wind (Singer and Shainberg 2004).

### 6.7.1 Soil Erosion and Cropland

In arid and semiarid areas, the major factors for the formation of vegetation patterns are the interaction between crop/vegetation and soil erosion processes (Ravi et al. 2008; Borgogno et al. 2009). Puigdefábregas (2005) highlighted that the geometry, scale, and spatial distribution of vegetated patches influence the spatial patterns of nutrients, moisture, and sediments that influence species composition and plant growth in arid and semiarid regions. D'Odorico et al. (2007) observed that the positive interaction between soil moisture and crops can increase the diversity in vegetation and soil and can play important roles in the emergence of stable states in dryland agriculture and vegetation pattern formation (Rietkerk and vandeKoppel 1997; Borgogno et al. 2009). Crop canopies may support the vegetation establishment by reducing evaporation and making soil wetter and by protecting soil from water and wind erosion, whereas drier soil without crop cover enhances soil erosion and results in soil degradation. Therefore, crop and cropping patterns can act as biological indicators of abiotic stress including runoff, flood, and draught (Ludwig et al. 2005).

Cropping pattern such as strip cropping and contour cultivation controls erosion by improving water absorption and soil fertility. Changes in the plant species and cropping pattern can accelerate the soil erosion processes by inducing sediment transport in degraded arid agricultural lands (van de Koppel et al. 2002). Thus, the information on the connection between plant spp., cropping pattern, and soil erosion processes is necessary to control soil erosion in the arid and semiarid climatic regions. Others farming practices such as crop rotation, strip cropping, contour cultivation, stubble mulching, etc. also protect the soil from rainfall and reduce soil erosion. Growing cover crops in agricultural fields can reduce erosion if barren land or dryland are having sufficient crop canopy during the rainy season. In dryland agriculture, pulse crop and other short-duration leguminous crops are suitable to protect the soil from erosion and degradation.

## 6.8 Impact of Changes in Cropland on Land Degradation and Desertification

Land degradation caused due to soil and vegetation degradation is the result of a complex interaction between socioeconomic and biophysical issues in tropics and subtropic regions. The negative changes in the biological, chemical, and physical properties of the soil are soil degradation, while the loss in plant species biodiversity or reduction in the number and composition of plant species is vegetation degradation.

Desertification is a phenomenon that is the negative result of anthropogenic activities and climatic variability causing land degradation in dry subhumid regions, semiarid and arid. In the twenty-first century, the major threats are the spread of desertification because of loss of biodiversity and reduction in the production capacity of cropland. The state changes happening within the cropland or other land use such as persistent alterations to crops or soils are key inducers of desertification in an arid and semiarid region. Seybold et al. (1999) reported that nowadays, vegetation in croplands is manipulated and negatively affects soil quality, soil fertility, soil organic carbon, and crop yields. There is a need to recover soil quality which improves soil productivity under given water and fertilizers (Lal 2001). Croplands play an important role in the maintenance of soil resilience by exhibiting equilibrium dynamics, using different management practices such as no-tillage cropping, conservation agriculture, residue retention, cover crops, and leguminous crops which recover the soil quality.

Due to changes in croplands for a long time, regime shifts can occur which ultimately affect the soil recovery of soil quality. The persistent changes such as alteration in soil texture, soil profile, soil fertility, and water-holding capacity occur due to soil erosion which is the main reason for regime shifts. This alteration in the soil profile properties adversely affects the organic carbon and other soil quality indicators that further reduce plant production (Lal 2001). Regime shifts along with reduced crop production can accelerate cropland abandonment, soil erosion, and continued desertification (Bakker 2005). Seybold et al. (1999) highlighted that regime shifts in cropland occur under similar soil conditions to those favored the regime shifts in rangelands.

The recovery of the soil profile, fertility, and soil quality can be promoted by adopting sustainable crop management practices and rangeland vegetation at minimal soil loss sites. Lal (2001) observed that soil erosion can permanently alter the soil properties which are salty, hardpans, and shallow. Thus, information about soil profile and plant species is necessary to evaluate the risk of the regime shift (rangeland-to-cropland) and to assess the potential for recovery of eroded croplands (Herrick et al. 2013).

## 6.9 Establishing Relationship between Land-Use Changes and Vegetation on Soil Erosion and Degradation

There is a need to establish clear relationship between land-use and land-cover changes on soil erosion and degradation. With the advancement in modeling and remote sensing technologies, it is easier to establish such relations. There are various models already available to qualify soil erosion, viz., the WEPP model of Flanagan and Nearing (1995); SWAT of Arnold et al. (1998), multiple logistic regression (MLR), radionuclide-based methods (Xinbao et al. 2003); the universal soil loss equation USLE of Wischmeier and Smith (1978), and its modified version RUSLE of Renard et al. (1997). RUSLE is developed with local modifications, and it has a database which helps for accurate estimation of soil erosion.

Remote sensing and GIS images are mostly used for quantification of land-use and land-cover changes. Mainly satellite imageries from Landsat 4, 5, 6, and 7, Landsat TM/OLI, Resourcesat 1 and 2, Sentinel 1 and 2, DEM (digital elevation model), and MODIS (Moderate Resolution Imaging Spectroradiometer) with spatial and temporal variation are accessible for studying LULC (Alam and Bhardwaj 2020). The satellite images are then processed with softwares like ERDAS Imagine 10. Further the land use is classified based on digital data. It includes the commonly used supervised and unsupervised methods. The unsupervised methods are K-means, ISODATA (Iterative Self-Organizing Data Analysis) clustering, Fuzzy C-means clustering, and self-organizing map (SOM) neural network method. Some commonly used supervised methods are maximum likelihood classifier (MLC), k-nearest neighbor (kNN), Mahalanobis distance, parallelepiped, minimum distance classifier, support vector machines (SVM), and random forest classifiers (RFC) (MohanRajan et al. 2020). LULC change analysis will be done by processing image with NDVI (normalized difference vegetation index). Other methods like machine learning methods like Classification and Regression Tree (CART), random forest (RF), and multivariate adaptive regression spline (MARS) were applied and compared for determining the LU/LC change (MohanRajan et al. 2020).

LU/LC classification is the method of labeling the pixels in the preprocessed satellite image for obtaining the classified images. Every pixel is considered as a unique entity and assigned to a particular class through pixel-based classification. Object-based classification is the collection of information from a group of related pixels, i.e., it grabs the pixels into graphical shapes, sizes, and other spatial properties. The land-use classification of the image is not completed until its accuracy assessment is done by ground truthing (MohanRajan et al. 2020).

Further image-processing softwares like ENVI, ArcGIS, IDRISI, ERDAS Imagine, Quantum GIS, and Google Earth software is used of delineating and processing map based on land-use systems. The land-use change detection of temporal variability can be assessed using post-classification comparison (PCC), which is done by pixel-by-pixel basis comparison of land-cover maps (Alam and Bhardwaj 2020).

The land-use maps are extrapolated with variables form models like RUSLE for getting status of soil erosion and land degradation on different classified land-use systems. There by clear linkage can be established between different land-use systems and land degradation. The main challenges of this methodologies are the following: acquisition of base maps of exact land area is challenging, preprocessing of georeferenced images is difficult, and errors in post-classification must be verified by ground truthing (Alam and Bhardwaj 2020).

## 6.10 Alternate Land-Use Strategies for Arresting Soil Erosion and Land Degradation

The relationship between land-use and land-cover changes with land degradation and soil erosion can be utilized for planning of alternative land-use systems. Land suitability classification and evaluation based on present changes in land-use pattern can be used for better land management, mitigation of land degradation, and designing land-use pattern that prevents environmental problems through segregation of competing land uses (Mazahreh et al. 2019). Optimization of land-use alternatives can be framed for improving agricultural production and livelihood (Mazahreh et al. 2019). It is imperative to mention that agricultural land-use planning involves soil-site suitability evaluation for crop growth under particular agro- climatic condition in order to utilize land resources in best possible manner. Changing land use under shifting cultivation must be brought under natural vegetation or forest region. Growing plantation crops can also provide livelihood in areas under shifting cultivation in northeast India (Ray et al. 2021). Reducing the spread of urbanization in croplands and forest areas must be done for preventing land degradation. Controlling cropland expansion and cultivation of cover crops in barren land are considered as alternative strategies. Improving present agricultural practices by conservation agriculture and no-tillage farming can be implemented for reduction of soil loss from croplands (Munoth and Goyal 2020). Governmental policy framework should also be changed considering changes in land use and the threat it poses to land degradation (Borrelli et al. 2020).

## 6.11 Conclusion

Land use is a crucial factor that influences not only agricultural production but also economy and ecosystem services. Changes in land use and land cover post-globalization and industrialization in India have resulted in accelerating soil erosion and desertification. To meet the increased demand of food for rapidly growing population, there was expansion in cropping area over forest area. The changes due to land use have different impacts on different agroecological zones. Some impacts even contradict each other. Use of remote sensing and GIS technologies helps us to establish relationship between land-cover changes and soil erosion. It also has its limitation of validation of land classification and difficulty in identifying micro-level changes within classified land use. Overall expansion of settlement area over croplands and expansion of agricultural area over forest area must be controlled. But strategizing for alternate land-use and agricultural management practice in a microscale must be done only after careful study of the existing land-use pattern, so as to formulate policy and plans to optimize land use for increasing agricultural production as well as arresting soil erosion and land degradation.

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# Management of Salt-Affected Soils for Increasing Crop Productivity

# 7

Pukhrambam Helena Chanu

## Abstract

Salt is present in the soil to some extent, but it will hamper crop growth and development when the concentration increases. In dryland soils, nutrients are not efficiently processed by microbes, the structure is weak, the salt content is high, and moisture retention is low. In arid and semiarid climate areas, soil salinity is the most common problem. Salt-accumulating soils can also develop in humid and sub-humid regions, particularly along the coast, where salt accumulation occurs as a result of seawater leaking into estuaries, rivers, and groundwater. Since large-scale irrigation efforts have been going on for decades, salt-affected soil problems have existed for a long time. Still, their magnitude and intensity have been increasing rapidly. Poor water management and unsound reclamation practices have aggravated the situation by developing irrigation systems without adequate drainage provisions. Approximately 952 million hectares of land worldwide are being degraded due to excessive exposure to salts, according to the FAO/UNESCO soil map, 1974. Identifying, reclaiming, and managing salt-affected soils are similar in their general characteristics and fundamental principles. Global climate variability, land and water degradation, biodiversity loss, and trade regulations have caused researchers and policymakers to be concerned about a growing population's food and nutritional security. It remains challenging to ensure sustainable agricultural productivity and a remunerative return to growers in the face of increasing competition for productive lands and freshwater resources. Although soil characteristics, climate, water availability, farm management capabilities, available resources, inputs, and economic incentives vary from place to place, so do the methods of soil reclamation, the

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extent, and the speed at which they are achieved. There is abundant helpful information about salt-affected soils in technical literature, yet too many efforts at reclaiming those soils have failed. These failures result in material losses and lost crop production due primarily to incorrect identification and reclamation methods. The negative effects of salinity have jeopardized food and nutritional security, causing environmental pollution and affecting farmers' soil health and income. In light of the above information, the following chapter will provide an overview of the effective management of salt-affected soil.

**Keywords**

Dryland soil · Salt-affected soil · Reclamation · Management

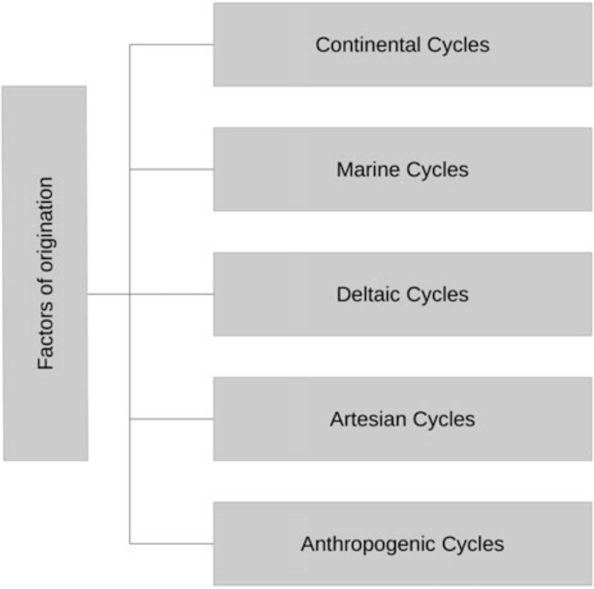
## 7.1 Introduction

Soils containing high levels of dissolved mineral salts negatively affect crop production (Wong et al. 2010). Salt-affected soils are chemically affected problem soil. The predominant salts which lead to the development of salt-affected soils comprise chlorides, sulphates, carbonates, bicarbonates of calcium ($Ca^{2+}$), magnesium ($Mg^{2+}$), and sodium ($Na^{+}$) (Qadir and Oster 2004). The excess salt build-up in the root zone can cause a partial or complete loss of soil fertility. In dryland soils, nutrients are not efficiently processed by microbes, the structure is weak, the salt content is high, and moisture retention is low. In arid and semiarid climate areas, soil salinity is the most common problem. Salt-accumulating soils can also develop in humid and sub-humid regions, particularly along the coast, where salt accumulation occurs due to seawater discharge into estuaries, rivers, and groundwater. Since large-scale irrigation efforts have been going on for decades, salt-affected soil problems have existed for a very long time. Global climate variability, land and water degradation, biodiversity loss, and trade regulations have caused researchers and policymakers to be concerned about a growing population's food and nutritional security. It remains challenging to ensure sustainable agricultural productivity and a remunerative return to growers in the face of increasing competition for productive lands and freshwater resources. Agriculture soils tend to have salinity mainly for two reasons: (i) shallow groundwater occurs in agricultural landscapes, which causes salt to accumulate at the soil surface (capillary action), and (ii) soils are sodic, which allows rainwater to accumulate little salt to the soil (Rengasamy 2002; Barrett-Lennard et al. 2016). In some cases, changes in land use can increase recharge to underlying aquifers, or they can increase the salt content in the soil, which is detrimental to the plants and microorganisms that form beneficial symbiotic associations with the plants (McFarlane et al. 2016). Approximately 952 million hectares of land worldwide are being degraded due to excessive exposure to salts, according to the FAO/UNESCO soil map, 1974. Globally, the process of identifying, reclaiming, and managing salt-affected soils is similar in its general characteristics and fundamental principles. Arable cropland soils tend to suffer from salinization and sodification, two common threats affecting their productivity.

The distribution of salt-affected soils is widespread and extensive in arid and semiarid regions. It is imperative to cultivate salt-affected soils to meet global food security challenges. In light of the above information, the following chapter will provide an overview of the effective management of salt-affected soil.

## 7.2 Factors for Development of Salt-Affected Soils

Five factors which are responsible for the development or origination of salt-affected soils are as below:



The accumulation and distribution of salts in the soil depend on the mobilities of different salts like NaCl, $Na_2SO_4$, $NaHCO_3$, $MgCl_2$, Mg $SO_4$, and $CaCl_2$ which are primary agents in soil salinization. Several factors can contribute to salt-affected soils, such as poor drainage, saline or sodic soil exposure as a result of erosion, parent soil material, long-term use of some fertilizers, low rainfall, or oil field activity.

## 7.3 Classification and Characteristics of Salt-Affected Soils

Classification of salt-affected soils is important to come about different management practices for a particular problem to increase crop productivity. Salt-affected soils are classified into three different classes, viz., (i) saline soils (ii) alkali soils, and (iii) saline-alkali soils (US Salinity Laboratory Staff 1954) (Table 7.1).

**Table 7.1** Classifications of salt-affected soils (US Salinity Laboratory Staff 1954)

| Classifications | $pH_s$ | Electrical conductivity ($EC_e$) | Sodium adsorption ratio (SAR) | Exchangeable sodium percentage (ESP) | Local name (India context) |
|---|---|---|---|---|---|
| Saline soils (solenchalk) | $<8.5$ | $>4\ dSm^{-1}$ | $<13$ | $<15$ | Reh, Thur |
| Alkali soils (solentz) | $>8.5$ | $<4\ dSm^{-1}$ | $>13$ | $>15$ | Usar, Kallar |
| Saline-alkali soils | $<8.5$ | $>4\ dSm^{-1}$ | $>13$ | $>15$ | Chopan |

### 7.3.1 Saline Soils

Saline soils are also known as "white alkali" soils as easily visible salt are deposited on the soil surface. The soluble salts which mainly constituted are chlorides and sulphates of calcium ($Ca^{2+}$), magnesium ($Mg^{2+}$), and sodium ($Na^+$). The dominant anions in saline soils are $Cl^-$, $SO_4^{2-}$, and $NO_3$. This soil class has a flocculated soil structure with good infiltration and drainage system.

### 7.3.2 Alkali Soils

Alkali soils are dominant with sodium saturation, adversely affecting plant growth and crop productivity. The dominant anions are $CO_3^{2-}$ and $HCO_3^-$. Also, $CaCO_3$ is commonly discovered in alkali soils, especially in arid and semiarid regions where continuous hydrolysis of $CaCO_3$ sustains the release of OH- ions in soil solution. Thus, the release of OH- ions results in higher pH in calcareous alkali soils than in noncalcareous alkali soils. These soils have deflocculated soil structure with poor drainage and infiltration system. These soils have black colour on the surface due to the deposition of dispersed and dissolved organic matter called "black alkali" or "slick spots".

### 7.3.3 Saline-Alkali Soils

Saline-alkali soils are developed due to both salinization and alkalization processes. These soils' dominant cations and anions are $Ca^{2+}$, $Mg^{2+}$, $K^+$, $Na^+$, $Cl^-$, $SO_4^{2-}$, $NO_3^-$, $CO_3^{2-}$, and $HCO_3^-$. They can achieve both characteristics of saline or alkali soils depending on the dominance of sodium or calcium. Generally, saline-alkali soils have a good soil structure with good water infiltration through the soil profile.

## 7.4 Reclamation and Management of Salt-Affected Soils

With the mindset of knowing that excess salts in the soil will hamper or prevent the growth and development of crops, there is a need for effective reclamation and specific management practices of affected areas soils to increase crop productivity. Reclamation aims to restore disturbed land to cultivable status, while management consists of all processes used to improve soil health. So, to execute the reclamation and management process, supplying an ample amount of drainage, replacing $Na^+$ ions from the soil-exchange complex, and leaching out of soluble salts below the root zone have to be verified. Management of salt-affected soil can be done through three different methods, viz., (a) physical methods, (b) chemical methods, and (c) biological methods.

### 7.4.1 Physical Methods

Most frequently complied physical methods include scraping, sanding, profile inversion, subsoiling, deep ploughing, flushing, leaching, and drainage system.

#### 7.4.1.1 Scraping

Scraping is mostly preferred by farmers, and it is a short-term method for improving the crop growth, which only scraped off the surface salt layer by using mechanical means. This method is disadvantageous under shallow water table conditions where salt can accumulate again due to evapotranspiration.

#### 7.4.1.2 Sanding

Sanding is the inclusion of sand in salt-affected soil to bring long-term change with increasing soil permeability, improving air-water relations in the root zone, and improving soil texture. In alkaline soils with high clay content, insufficient sand may cause problems because of its cementing effect. Sand is therefore needed in large quantities to study cementing effects.

#### 7.4.1.3 Profile Inversion

A profile inversion method needs to be applied to soils with good surface soil but bad soil below some depth (sodic soil, saline soil, etc.). This method involves keeping the good soil on the surface while inverting a saline/sodic subsoil. Due to its complexity, this method is generally not used by farmers.

#### 7.4.1.4 Deep Ploughing and Subsoiling

In deep ploughing and subsoiling methods, layers existing at various depths in the soil profile are broken down to improve drainage in the soil and transport salts dissolved in water to deeper layers.

Flushing is a desalinization method where the salts accumulated on the surface are washed out by water. With the decrease in saline concentration, its efficiency decreases causing low applicability.

#### 7.4.1.5 Leaching

Leaching is the most effective technique for removing salt from the soil's root zone. In this method, water is usually ponded on the soil surface and allowed to percolate into the soil, which will enable it to leach (Horneck et al. 2007). Uniform application of water and its percolation through the root zone soil describes leaching effectiveness. Before starting the leaching process, land levelling is the most crucial step to be followed. If continuous ponded conditions are maintained, approximately 80% of soil salts are normally eliminated by leaching water per metre of soil depth. The most efficient leaching method is the basin furrow method.

#### 7.4.1.6 Drainage System

In saline soils, a drainage system is constructed to balance water and salt on both surface and subsoil. Surface drainage and sub-surface drainage are two types of the drainage system. The most common drainage systems are horizontal relief drains, such as open ditches, buried tiles, perforated pipes, or, in some cases, pumped drainage wells. The essentiality for constructing either surface or sub-surface drainage systems has to be carried out in terms of the nature of the soil, groundwater conditions, climate cropping patterns, economic considerations, and others.

### 7.4.2 Chemical Methods

Alkali/sodic soils ($Na_2CO_3$ and $NaHCO_3$) which upon hydrolysis produces alkalinity. The chemical amendments used for the reclamation of these soils are classified as:

(a) Soluble salts of calcium like gypsum ($CaSO_4.2H_2O$), $CaCl_2$, phospho-gypsum.
(b) Sparingly soluble calcium salts like calcite and $CaCO_3$.
(c) Acid or acid formers like sulphur, $H_2SO_4$, sulphates of Fe and Al, pyrites, and lime-sulphur.

Each of these amendments is most effective when alkaline-earth carbonates (specifically $CaCO_3$) are present in the soil. The most economical and generally used chemical amendment is gypsum. A disc or cultivator can put gypsum in the top 10 cm of soil by broadcasting it and incorporating it.

### 7.4.3 Biological Methods

Biological methods include the amendment of organic manures, which improves the microbial activity in the soil. Some of the essential biological methods are green manuring, the inclusion of crop residues, incorporation of FYM, press mud, microbial consortium, and other organic materials. Adding arbuscular mycorrhizal fungi (AMF) and phytoremediation using halophytic plants, like *Chenopodium album*, *Suaeda australis*, *Salsola vermiculata*, etc. and cultivation of dill (*Anethum graveolens*) are suggested.Apart from all these discussed methods, other management practices like evading excessive fertilizer use after leaching of salts, establishing cover crops to reduce erosion, and growing salt-tolerant crop varieties are followed. For more effectiveness and sustainability, the combination of all the different methods studied should be applied. Therefore, it will bring a high opportunity for better productivity in salt-affected soils. Furthermore, numerous studies have demonstrated that biochar improves physical, chemical, and biological characteristics of salt-affected soils (Lashari et al. 2013; Lashari et al. 2015; Thomas et al. 2013; Chaganti et al. 2015; Chaganti and Crohn 2015; Hammer et al. 2015; Kim et al. 2016; Akhtar et al. 2015a, b, c; Lu et al. 2015; Amini et al. 2016; Sun et al. 2017; Ali et al. 2017). Biochar has been shown to reduce SAR/ ESP in saline-sodic and sodic soils (Wu et al. 2014; Chaganti et al. 2015; Chaganti and Crohn 2015; Amini et al. 2016; Lashari et al. 2013, 2015; Drake et al. 2016; Kim et al. 2016; Luo et al. 2017; Sun et al. 2017). Biochar's potential to affect plant growth in salt-affected soils, however, must be thoroughly explored. The results of such studies will assist in maximizing potential benefits associated with the use of biochar in soil as well as minimizing adjustments.

## 7.5 Approaches for Strengthening both Productivity and Income of Farmers

Increasing productivity for increasing the income of farmer is a necessary step by maintaining the soil health status. For reclamation of the affected soils, ICAR-CSSRI has developed techniques to make the soil from unproductive to productive (Chinchmalatpure 2017).

The techniques are listed as:

- Reclamation of sonic soil using gypsum technology.
- Amelioration of waterlogged saline irrigated land by sub-surface drainage technology.
- Cultivation of salt-resistant crops like dill, *Salvador persica* on highly saline soils.
- Groundwater recharge for harnessing rainwater in farmer's field.
- Models of Integrated farming system for salt-affected black soils.

## 7.6 Conclusions

There is much helpful information about salt-affected soils in technical literature, yet too many efforts at reclaiming those soils have failed. Due primarily to incorrect identification and reclamation methods, these failures result in material losses and lost crop production. So, there is a need to join hands with farmers and other agricultural-related institutes like KVK, ICAR, and NGOs to provide more awareness to restore and reclaim the affected soil from further deterioration. The harnessing of proper management methods for a particular salt-affected soil should be carried out sustainably and effectively. Intensive studies on management and reclamation methods are still needed for the benefits of the farmer as well for soil heath. Introduction of different salt-tolerant cultivars and models of integrated farming system can help in harnessing the affected soils. From the above discussions, it can conclude that the excess exchangeable salts present in the soil should be effectively removed by implementing all the methods together to increase the crop productivity.

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# 8

# Role of Water Harvesting and Supplemental Irrigation in Enhancing Agriculture Productivity of Dryland under Climate Change

Venkatesh Gaddikeri, Malkhan Singh Jatav, Md Majeed Pasha, Kishor Gavhane, Ajay N. Satpute, Truptimayee Suna, Jitendra Rajput, and A. K. Mishra

## Abstract

Water resources availability for agriculture use has decreased in recent past due to competition from various water sectors. Dryland agriculture contributes significantly to global food production. Climate change has impacted the availability and distribution of water resources, as well as the productivity and sustainability of dryland agriculture. In the current chapter, various aspects of water harvesting techniques, viz., in-situ and ex-situ, conventional and modern technique have been discussed. Furthermore, significance of supplemental irrigation in dryland agriculture to mitigate detrimental impact of climate change on land and water productivity has been described. Water harvesting and supplemental irrigation techniques have enormous potential to increase crop yield and could be critical measures for climate change-resilient agriculture. Hence, adoption of water conservation measures in dryland agriculture system is necessary to ensure sustainable development growth.

**Keywords**

Catchment system · Climate resilience · Irrigation · Moisture · Rooftop

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## 8.1 Introduction

Dryland farming antedates history; use of the term in its present form and meaning probably began in Utah, the USA, around 1863 and credits John A. Widtsoe as being the pioneer of dryland farming research (Hegde and Singh 1995). Widtsoe defined dryland farming as “the profitable production of useful crops without irrigation on areas that receive rainfall of less than 500 mm annually” and said that the definition could be extended to include areas receiving up to 750 mm annual rainfall where its distribution was unfavorable. The management of other lands in an area is not included in this definition since it only refers to land used to raise crops. Even within the United Nations, the word “drylands” is defined in a variety of ways, although the climatic aridity index is the most widely used. One such index proposed in the World Map of Arid Zones (UNESCO 1977) defines climate zones by dividing annual precipitation (P) by annual potential evapotranspiration (PET). Based on this index, climate zones are categorized as hyper-arid ($P/PET < 0.03$), arid ($0.03 < P/PET < 0.20$), semiarid ($0.20 < P/PET < 0.50$), and subhumid ($0.50 < P/PET < 0.75$). However, it’s important to note that there is probably no classification system that can be universally applied, and each area should be considered on its own merits. National and regional classifications that reflect local characteristics have also been developed to aids in decision-making processes.

Very often, the words dry farming, dryland agriculture, and rainfed agriculture are used synonymously to indicate similar farming situation. Clearly, they exclude irrigation. Rainfed farming, which includes both dry and dryland farming, has also seen a major shift in its definition. Earlier for more than 60 years, the notion of dry farming relied on minimal annual rainfall (less than 500 millimeters) (Govindan et al. 2003).

In modern concept, dryland region is one in which the moisture balance is constantly on the negative side. Evapotranspiration is more than precipitation on a yearly basis. The quantity of rainfall has no bearing on dryland agriculture. Differentiating factors include rainfall, the amount of water available to a crop, and its growth season in a dryland environment. There is less than 750 mm of rain for dryland farming and more than 750 mm of rain for rainfed farming. With less water available in dryland farming and plenty in rainfed farming, there is a shorter growth season (days) than in rainfed farming.

Globally, about 41.3% of the Earth’s surface is covered by dryland farming. Developing nations make up 72% of the population. 228 million hectares of India’s territory are classified as dryland, which includes arid, semiarid, and dry subhumid conditions. About 60–70% of the world’s basic foods are produced by rainfed agriculture, which covers about 80% of the world’s agricultural land (Kumar et al. 2019; Van der Esch et al. 2022). It is evident that there was, there is, and there will be climate variability at global, regional, and local levels. Since climate is closely related to human activities and economic development including agricultural system, especially in dryland areas, there is a serious concern about its stability (Singh et al. 2021). Monsoon rains are critical to agricultural output in dryland regions, and climate change poses a significant threat. Eventually, it has an impact on the region’s food, water, and poverty security. Dryland agricultural locations are diverse in terms of climate and soil conditions; however, there are several concerns which may be identified. Annual crop output in dryland agricultural locations is constantly constrained by water shortage and soil erosion and becomes a significant problem due to both precipitation and temperature variability (Peterson 2018).

As a result of the unpredictable and spatiotemporal variability of rainfall and temperature caused by climate change, dryland may become highly moisture-stressed, resulting in a variety of monsoon-related problems, such as delayed onset, early withdrawal, and prolonged dry periods (water scares). Improved precipitation use efficiency is necessary for effective management of dryland agriculture and long-term sustainability of the land (Turner 2004). That's why it's suggested that (1) save and store precipitation, (2) cut down on evaporation, and (3) use kinds of drought-tolerant crops. This chapter focuses on two elements of dryland agriculture's water management for enhancing productivity: (1) capturing and storing precipitation (water harvesting) and (2) efficiently using stored water (supplemental irrigation) to improve agricultural productivity.

## 8.2 Role of Climate-Resilient Water Management in Dryland Agriculture

### 8.2.1 Concept and Component of Water Harvesting

Water harvesting is one of the key components and integral part of sustainable land and water management in successful rainfed farming in semi-dryland agriculture. The basic principle of water harvesting is to capture precipitation falling in one area and transfer it to another, thereby increasing the amount of water available in the latter. Harvesting surplus runoff using water harvesting structures and recycling the same for providing supplemental irrigation to kharif crops, pre-sowing irrigation to rabi crops has proved to be the most successful technologies for adoption in agriculture (Boers and Ben-Asher 1982; Pacey and Cullis 1986). Water harvesting concept is becoming more relevant now in view of the recent increase in the extreme events wherein heavy rainfall is occurring in few days followed by long dry spells. Under such circumstances, the only answer is harvesting the surplus runoff during high rainfall events and using the same during dry spells for critical irrigation (Pandey et al. 2003). The basic components of a water harvesting system are a catchment or collection area, the runoff conveyance system, a storage component, and an application area. In some cases, the components are adjacent to each other; in other cases they are connected by a conveyance system. The storage and application areas may also be the same, typically where water is concentrated in the soil for direct use by plants (Morey et al. 2016). The different components of water harvesting components are discussed below:

(A) **Catchment or collection area**: This is where rain in the form of runoff is harvested. The catchment may be as small as a few square meters or as large as

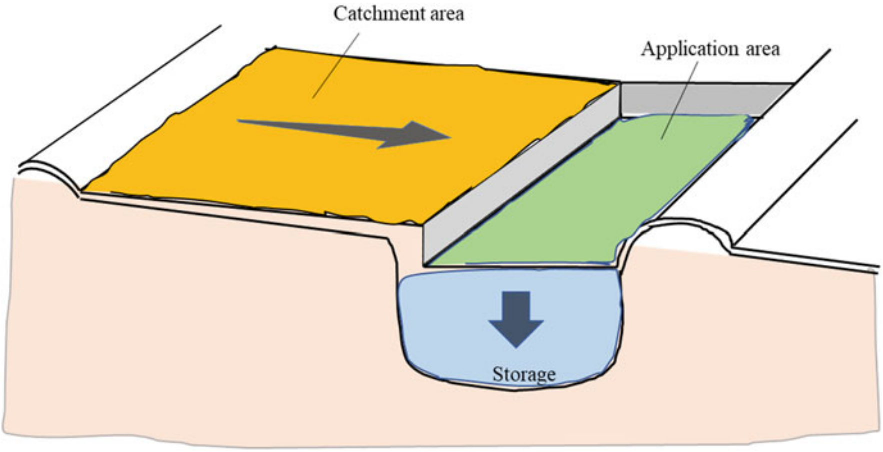


**Fig. 8.1** Different components of water harvesting

several square kilometers. It may be a rooftop, a paved road, compacted surfaces, rocky areas or open rangelands, cultivated or uncultivated land, and natural slopes.

(B) **Conveyance system:** Where runoff is conveyed through gutters, pipes (in case of rooftop WH) or overland, rill, gully, or channel flow and either diverted onto cultivated fields (where water is stored in the soil) or into specifically designed storage facilities (Fig. 8.1).

(C) **Storage component:** The harvested runoff water is stored until it is used by people, animals, or plants. Water may be stored in the soil profile as soil moisture, or aboveground (jars, ponds, or reservoirs), or underground (cisterns), or as groundwater (near-surface aquifers). There, where concentrated runoff is directly diverted to fields, the application area is identical to the storage area, as plants can directly use the accumulated soil water. A great variety of designed storage systems keep the water until it is used either adjacent to the storage facilities or further away.

(D) **Application area or target:** The harvested water is put into use either for domestic consumption (drinking and other household uses), for livestock consumption, or for agricultural use (including supplementary irrigation).

## 8.2.2 Water Harvesting Techniques

### 8.2.2.1 Micro-Catchment System

Micro-catchment is a specially contoured area with slopes designed to increase runoff from rain and concentrate it in a planting basin where it infiltrates and is effectively “stored” in the soil profile. The water is available to plants but protected from evaporation. Micro-catchment systems provide many advantages over other

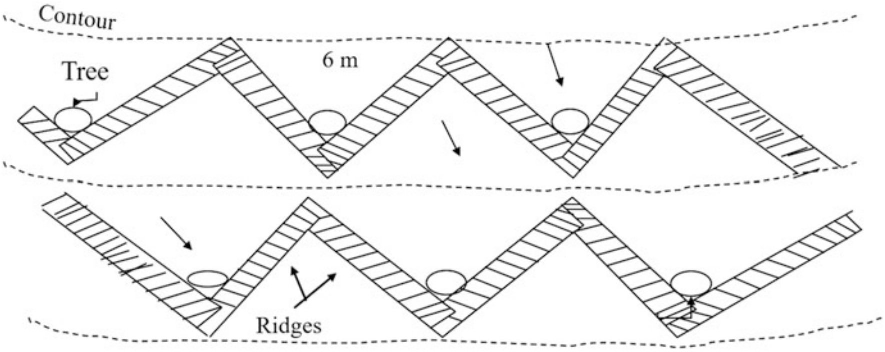


**Fig. 8.2** Micro-catchment runoff farming water harvesting

irrigation schemes (Fig. 8.2). They are simple and inexpensive to construct and can be built rapidly using local materials and manpower. The runoff water has a low salt content, and as it does not have to be transported or pumped, it is relatively inexpensive. Micro-catchments enhance leaching and often reduce soil salinity (Oweis and Hachum 2006).

#### 8.2.2.2 Macro-Catchment System

Macro-catchment water harvesting systems usually consist of four components such as catchment area, runoff conveyance system, storage system, and application area. In the catchment area, rainwater runoff is collected from compacted surfaces, including hillsides, roads, rocky areas, open rangelands, cultivated and uncultivated land, and natural slopes. Mostly macro-water harvesting practices have a catchment area of less than 2 ha, in some cases; however, runoff is collected from catchments as large as 200 ha (Adham et al. 2016). The runoff is conveyed through overland, rill, gully, or channel flow and either diverted onto cultivated fields (where water is stored in the soil) or into specifically designed storage facilities. Where concentrated runoff is directly diverted to fields, the application area is identical with the storage area, as plants can directly use the accumulated soil water. The application or cropping area is either terraced or located in flat terrain. The ratio of the catchment to the application area (usually cultivated) varies between 10:1 and 100:1 (Datta 2019). In the second case, a great variety of designed storage systems keep the water until it is used either adjacent to the *storage* facilities or further away (involving a conveyance system). The classification of technologies into macro-water harvesting is not always straightforward. It depends on the catchment size, the duration of rainfall event, and concentration of runoff which is tapped harvest from the channel flow. Macro-water harvesting collects sheet and rill flow and short-distance channel flow. The harvested water is mainly used for crop and livestock production but also for domestic use, depending on the quantity and quality (Rango and Havstad 2009). Macro-water harvesting practices are applicable in arid and semiarid to subhumid zones where it is necessary to store water to bridge the dry season or to mitigate the impact of dry spells. They're often situated in natural or man-made depressions, or even in ephemeral riverbeds. Macro-water harvesting is required in areas with long dry periods and where rainfall fluctuates widely over time.

#### 8.2.2.3 Indian Traditional Water Harvesting Structures

(A) Kul: Kuls are water channels found in precipitous mountain areas. These channels carry water from glaciers to villages in the Spiti Valley of Himachal Pradesh. Where the terrain is muddy, the kul is lined with rocks to keep it from becoming clogged. In the Jammu and Ladakh regions too, similar irrigation systems called kuls are found (Fig. 8.3).

(B) Naula: Naula is a surface water harvesting method typical to the hill areas of Uttaranchal. These are small wells or ponds in which water is collected by making a stone wall across a stream.

(C) Khatri*:* Khatris are structures, about 10 × 12 feet in size and 6 feet deep carved out in the hard rock mountain. The specially trained masons construct them at a cost of Rs 10,000–20,000 each. These traditional water harvesting structures are found in Hamirpur, Kangra, and Mandi districts of Himachal Pradesh. Khatris are mainly used for animals and house purposes. In which rainwater is collected from the roof, and other used for human consumption in which rainwater is collected by interstices, crevices. Interestingly, khatris are owned by private (individual, and community) and government khatris as well, which are maintained by the Panchayat (Sharma and Kanwar 2009).

(D) Kuhl: Kuhls are a traditional irrigation system in Himachal Pradesh; surface channels are diverting water from natural flowing streams (khuds). A typical community kuhl services 6–30 farmers, irrigating an area of about 20 ha. The system consists of a temporary headwall (constructed usually with river boulders) across a khud (ravine) for storage and diversion of the flow through a canal to the fields. By modern standards, building kuhls was simple, with boulders and labor forming the major input. The kuhl were provided with moghas (kuchcha outlets) to draw out water and irrigate nearby terraced fields. The water would flow from field to field and surplus water would drain back to the khud.

The kuhls were constructed and maintained by the village community. At the beginning of the irrigation season, the kohli (the water tender) would organize the irrigators to construct the headwall, repair the kuhl, and make the system operational. The kohli played the role of a local engineer. Any person refusing

**Fig. 8.3** Kuls water channels found in Ladakh region

to participate in construction and repair activities without valid reason would be denied water for that season. Since denial of water was a religious punishment, it ensured community participation and solidarity. A person was also free to participate by providing a substitute for his labor. The kohli also distributed and managed the water.

(E) Zabo: The zabo (the word means "impounding runoff") system is practiced in Nagaland in northeastern India. Also known as the ruza system, it combines water conservation with forestry, agriculture, and animal care. Villages such as Kikruma, where zabos are found even today, are located on a high ridge. Though drinking water is a major problem, the area receives high rainfall (Rao et al. 2012). The rain falls on a patch of protected forest on the hilltop; as the water runs off along the slope, it passes through various terraces. The water is collected in pond-like structures in the middle terraces; below which are cattle yards, and toward the foot of the hill are paddy fields, where the runoff ultimately meanders into.

(F) Eri: Approximately one-third of the irrigated area of Tamil Nadu is watered by eris (tanks). Eris have played several important roles in maintaining ecological harmony as flood-control systems, preventing soil erosion and wastage of runoff during periods of heavy rainfall, and recharging the groundwater in the surrounding areas. The presence of eris provided an appropriate microclimate for the local areas. Without eris, paddy cultivation would have been impossible. Till the British arrived, local communities maintained eris. Historical data from Chengalpattu district, for instance, indicates that in the eighteenth century, about 4–5% of the gross produce of each village was allocated to maintain eris and other irrigation structures. Assignments of revenue-free lands, called manyams, were made to support village functionaries who undertook to maintain and manage eris. These allocations ensured eri upkeep through regular desilting and maintenance of sluices, inlets, and irrigation channels. The early British rule saw disastrous experiments with the land tenure system in quest for larger land revenues. The enormous expropriation of village resources by the state led to the disintegration of the traditional society, its economy, and polity. Allocations for maintenance of eris could no longer be supported by the village communities, and these extraordinary water harvesting systems began to decline (Prasad et al. 2015; More 2020).

(G) Ooranis**:** The tanks, in South Travancore, though numerous, were in most cases ooranis containing just enough water to cultivate the few acres of land dependent on them. The irregular topography of the region and the absence of large open spaces facilitated the construction of only small tanks unlike large ones seen in the flat districts of Tamil Nadu (Raghavan and Eslamian 2021; Starkl and Essl 2012).

(H) Apatani: This is a wet rice cultivation cum fish farming system practiced in elevated regions of about 1600 m and gentle sloping valleys, having an average annual rainfall about 1700 mm and also rich water resources like springs and streams. This system harvests both ground and surface water for irrigation. It is practiced by Apatani tribes of Ziro in the lower Subansiri district of Arunachal Pradesh. In Apatani system, valleys are terraced into plots separated by 0.6-meter-high earthen dams supported by bamboo frames. All plots have inlet and outlet on opposite sides. The inlet of low-lying plot functions as an outlet of the high-lying plot. Deeper channels connect the inlet point to outlet point. The terraced plot can be flooded or drained off with water by opening and blocking the inlets and outlets as and when required. The stream water is tapped by constructing a wall of 2- to 4 m high and 1 m thick near forested hill slopes. This is conveyed to agricultural fields through a channel network (Bhattacharya 2015).

#### 8.2.2.4 Modern Methods of Water Harvesting Structures

(A) **Pits:** Recharge pits are constructed for recharging the shallow aquifer. The aquifer is porous, water-saturated layers of sand, gravel, or bed rock that can yield significant or usable amount of water. These are constructed 1–2 m wide, 1–1.5 m deep which are back filled with boulders, gravels, and coarse sand (Machiwal et al. 2004).

(B) **Trenches:** These are constructed when the permeable rock is available at shallow depth. Trench may be 0.5–1 m wide, 1–1.5 m deep, and 10–20 m long depending upon the availability of water. These are back filled with filter materials (Bouwer 2002).

(C) **Dug wells:** Existing dug wells may be utilized as recharge structure, and water should pass through filter media before putting into dug well.

(D) **Hand pumps:** The existing hand pumps may be used for recharging the shallow/deep aquifers, if the availability of water is limited. Water should pass through filter media to avoid chocking of recharge wells.

(E) **Recharge wells:** Recharge wells of 100–300 mm diameter are generally constructed for recharging the deeper aquifers, and water is passed through filter media to avoid choking of recharge wells (Lohani et al. 2021).

(F) **Recharge shafts:** For recharging the shallow aquifer which is located below clayey surface, recharge shafts of 0.5–3 m diameter and 10–25 m deep are constructed and back filled with boulders, gravels, and coarse sand (Yadav et al. 2012; Kambale et al. 2017).

(G) **Lateral shafts with bore wells:** For recharging the upper as well as deeper aquifers, lateral shafts of 1.5–2 m wide and 10–30 m long depending upon availability of water with one or two bore wells are constructed. The lateral shaft is back filled with boulders, gravels and coarse sand.

(H) **Recharging of dug wells and abandoned tube wells:** In alluvial and hard rock areas, there are thousands of wells which have either gone dry or whose water levels have declined considerably. These can be recharged directly with rooftop runoff. Rainwater that is collected on the rooftop of the building is diverted by drainpipes to a settlement or filtration tank, from which it flows into the recharge well (bore well or dug well). If a tube well is used for recharging, then the casing (outer pipe) should preferably be a slotted or perforated pipe so that more surface area is available for the water to percolate. Developing a bore well would increase its recharging capacity (developing is the process where water or air is forced into the well under pressure to loosen the soil strata surrounding the bore to make it more permeable). If a dug well is used for recharge, the well lining should have openings (weep holes) at regular intervals to allow seepage of water through the sides. Dug wells should be covered to prevent mosquito breeding and entry of leaves and debris. The bottom of recharge wells should be desilted annually to maintain the intake capacity (Brar et al. 2019; Gupta et al. 2019).

(I) **Percolation pit:** Percolation pits, one of the easiest and most effective means of harvesting rainwater, are generally not more than 60 × 60 × 60 cm pits, (designed on the basis of expected runoff as described for settlement tanks), filled with pebbles or brick jelly and river sand, covered with perforated concrete slabs wherever necessary.

(J) **Recharge trenches:** A recharge trench is a continuous trench excavated in the ground and refilled with porous media like pebbles, boulders, or broken bricks. A recharge trench can be 0.5–1 m wide and 1–1.5 m deep. The length of the recharge trench is decided as per the amount of runoff expected. The recharge trench should be periodically cleaned of accumulated debris to maintain the intake capacity. In terms of recharge rates, recharge trenches are relatively less effective since the soil strata at depth of about 1.5 m is generally less permeable. For recharging through recharge trenches, fewer precautions have to be taken to maintain the quality of the rainfall runoff. Runoff from both paved and unpaved catchments can be tapped.

(K) **Rooftop rainwater harvesting:** A simple structure where the roof is used as a support for installing catchment pipes through which the rainwater flows and is eventually stored in ground level containers for direct use or recharged into groundwater.

(L) **Subsurface dam:** A subsurface dam intercepts or obstructs the flow of an aquifer and reduces the variation of the level of the groundwater table upstream of the dam. It is built entirely under the ground (Raju et al. 2006).

(M) **Sand storage dam:** It is constructed aboveground. Sand and soil particles transported during periods of high flow are allowed to deposit behind the dam, and water is stored in these soil deposits (Fig. 8.4). The sand storage dam is constructed in layers to allow sand to be deposited, and finer material is washed downstream. A groundwater dam can also be a combination of these two types. When constructing a subsurface dam in a riverbed, one can increase the storage volume by letting the wall of the dam rise over the surface, thus causing additional accumulation of sediments (Hut et al. 2008). Similarly, when a sand storage dam is constructed, it is necessary to excavate a trench in the sand bed in order to reach bedrock, which can be used to create a subsurface dam too.

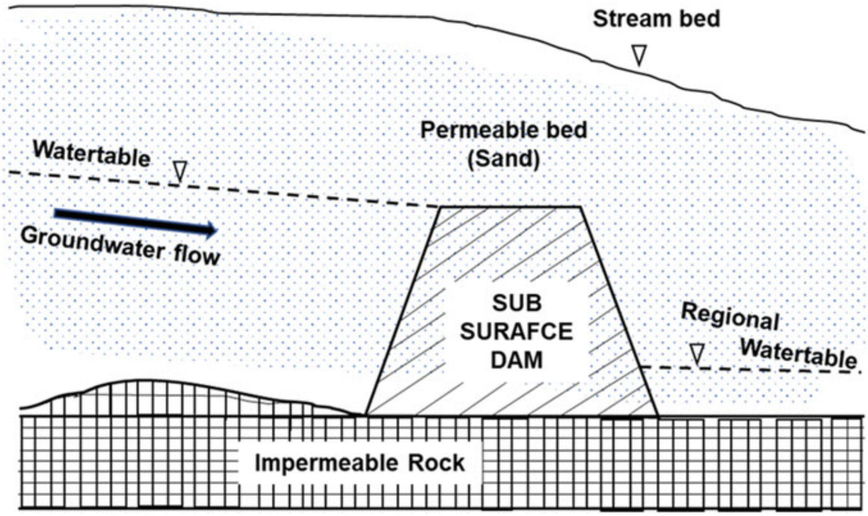


**Fig. 8.4** Subsurface dam

### 8.2.3 Water Storage and Purpose

*Water stored in the soil* is directly used for plant and crop growth prolonging the growing season and bridging the dry spells allowing to produce crops and yields without demanding irrigation systems. Designed *storage facilities* cover a broad range of open or closed structures. *Open storage* include *farm ponds* and different types of *dams* (often earth dams). *Closed structures* can be *groundwater dams* or *above* and *belowground tanks or reservoirs*. Such storage structures are often characterized by multipurpose use, prioritizing domestic and livestock consumption. During dry spells, sometimes the water may be used for supplementary irrigation.

## 8.3 Supplemental Irrigation

The rainfed production system is the world's predominant production system as it accounts for 60% and 80% of global food production and cropping area, respectively (Reynolds et al. 2007). The main factor that limits crop production in rainfed and dryland areas is water availability. Rainwater harvesting in such areas has become a promising solution to overcome the problem. Water harvested in the rainwater harvesting structures can be put to different uses. It includes agriculture, livestock, landscaping, recreational domestic use, and sometimes drinking after purification. In the agriculture sector, harvested rainwater is mainly used for irrigation of the crops. Rainwater harvesting is mainly practiced in the semiarid and arid regions, where water availability to crops is a permanent constraint for food production. With the limited water availability, farmers can only provide irrigation at the critical crop growth stages. Such irrigation from the harvested rainwater at critical growth stages is called supplemental irrigation. According to ICID supplemental irrigation is the "the addition of small amounts of water to essentially rainfed crops during times when rainfall fails to provide sufficient moisture for normal plant growth, to improve and stabilize yields."

### 8.3.1 Characteristics of Supplemental Irrigation (SI)

- Water is applied to rainfed crops which is normally produced without irrigation.
- It is applied only when rainfall is inadequate, because rainfall is the prime source of water for rainfed crops.
- The amount and timing of SI are not meant to provide water stress-free conditions over the growing season but to provide enough water during the critical stages of crop growth to ensure optimal yield in terms of yield per unit of water (Oweis 1997).

## 8.4 Role of Water Harvesting and Supplemental Irrigation in Enhancing Agricultural Productivity of Drylands under Climate Change

### 8.4.1 Increase in Water Productivity

The water availability in the future for agriculture is going to be scarce due to many factors such as additional pressure of population, competition for water from other sectors, and climate change. Due to the limited availability of water resources, per unit productivity of water in agriculture needs to be enhanced to meet the increasing demand for food production as well as to cope with climate change. Water productivity is the amount of grain or biomass produced per unit of water. Many efforts were made to increase the water productivity from conventional irrigation, and they are still in practice. Supplemental irrigation hand has proved to increase the water productivity in agriculture (ICARDA 2022). With supplemental irrigation, water is mainly provided at the critical growth stages of crops, which avoids water stress in plants at prime period. By avoiding the water stress, the yield of the crop is maintained even with the limited water, and hence the amount of grain per unit of water, i.e., water productivity, is higher (Nangia and Oweis 2016). When supplemental irrigation is incorporated with the other field management practices such as soil preparation, nutrient management, pest and disease management, and the choice of suitable crop varieties, it will help in improving water productivity as compared to the other alone application of supplemental irrigation (Gadédjisso-Tossou et al. 2018). However, very high application of nitrogen is detrimental to water productivity when combined with supplemental irrigation. Water consumption in peanuts initially increased and subsequently decreased with an increase in nitrogen application rates under supplemental irrigation (Xia et al. 2021). Even though supplemental irrigation increases the total yield, yield per unit of water gradually decreases, due to higher nitrogen application in the field. Hence, the combination of optimum nitrogen application and depth of supplemental irrigation that provide increased water productivity needs to be formulated for a particular crop. In the light of the increasing pressure on water resources and uncertainty due to climate change, supplemental irrigation plays a dominant role to increase water productivity from supplemental irrigation to providing food and sustaining livelihoods in dryland areas (Kemeze 2020).

### 8.4.2 Increase in Crop Productivity

Along with water productivity, supplemental irrigation also improves crop productivity. It is the crop yield per unit area. Dry matter accumulation is the basis for crop yield formation. The formation of dry matter in crops is mainly governed by nitrogen nutrition (Xing et al. 2015; Zheng-feng et al. 2016). Supplemental irrigation applied at the proper moisture content of soil intensifies the accumulation of soil nitrate-nitrogen. Supplemental irrigation is more beneficial to the effective conversion of dry matter from roots to other plant components, and it also limits the redundant growth of roots. In addition, it significantly increases the total amount of nitrogen accumulation, which has a positive effect on the reproductive growth period. It promotes the nitrogen transformation in the leaves which is helpful to the development of the economic yield of a crop (Xia et al. 2021). Supplemental irrigation significantly improves the crop yield or biomass yield, harvest index, and water-use efficiency (WUE). It has been reported that there's a 15%, 25%, and 64% increase in harvest index, biomass, and rice grain yield in transplanted rice with 3 cm ponding water by supplemental irrigation than dry planted rainfed rice (Molla et al. 2021), while Man et al. (Man et al. 2016) reported an 18% and 46% increase in WUE and wheat grain yield for supplemental irrigation at 40 cm soil depth. From a perspective of plant physiology, previous studies in the field of plant physiology have demonstrated that a sufficient water supply can effectively regulate the cell osmotic potential which promotes the opening of stomata. The increased stomatal opening is conducive to a rise in transpiration and consequently enhances soil water and nutrient uptake. Therefore, supplemental irrigation can improve crop quality through improvements in soil-plant water transport and physiological regulation (Xia et al. 2021). Even though supplemental irrigation is beneficial in increasing the crop yield and crop water productivity, it is very important to plan the optimum depth of water and the timing of application. However, an optimal strategy is difficult to determine in advance because of the spatial and temporal variability of rainfall. Yet, it can be scheduled to maintain and ensure minimum soil moisture availability during critical crop growth stages for ensuring timely sowing and achieving optimal yield (Nangia and Oweis 2016). Supplemental irrigation could become more important due to changing climate where there is greater rainfall uncertainty and a higher frequency of droughts.

### 8.4.3 Deficit Supplemental Irrigation

The irrigation with this stored water can be applied in full amount as well in deficit amount of the crop water requirement. Like normal irrigation, supplemental irrigation can also be applied in full amount or deficit amount of crop water requirement. In deficit supplemental irrigation, a predesigned portion of the full crop water requirement is applied. With this, high irrigation as well as rainwater productivity is achieved since this irrigation is based on calculated allowable water stress. Many times, this allowable water stress is proportional to the irrigation level, i.e., full irrigation is free from the moisture stress. The permissible water stress also results in the reduction of the yield of a crop. Getachew and his team reported an average yield difference of 1 $t\ ha^{-1}$ for sorghum between deficit and full supplemental irrigation (Getachew et al. 2021). However, this practice of deficit supplemental irrigation demands precise knowledge of a particular crop's response to water because the drought tolerance is influenced by the species, crop cultivar, and growth stage also (Tavakoli et al. 2010; Karrou and Oweis 2012; Hessari and Oweis 2021).

### 8.4.4 Supplemental Irrigation in Protected Cultivation

In protected cultivation of crops, the production factors are controlled to a greater extent than the open field conditions, and hence more yield is obtained. Under the threat of global warming and climate change, when the growing conditions for crops are becoming more and more adverse, the raising of crops in protected cultivation ensures increased production. But it is also not free from the water constraint. The supplemental irrigation can also be applied to crops raised in protected cultivation.

### 8.4.5 Optimization of Supplemental Irrigation

The yield of the field crop depends upon many factors. Out of all these factors, the timing of the availability of water and nutrient is the most important. These factors need to be optimized for beneficial results from supplemental irrigation. Under the practice of supplemental irrigation, water is more difficult to control and manage owing to the randomness of rainfall. In the case of conventional irrigation, nowadays we have packages of different management options under various biophysical conditions which guide the farmers in selecting the types and doses of nutrients required and also timing for application to achieve higher yield. But this is not the case with supplemental irrigation. In this case, even if we assume all production inputs such as nutrient availability, timing of tillage practices, etc., to be satisfactory, the water availability is the constraint, and hence it is essential to determine the water production functions for maximizing the profit. For the development of this variable function, well-designed long-term field experiments under supplemental irrigation conditions are required. Since we have all the production factors in sufficient quantity and only water availability is the constraint in this experiment, all other production inputs are kept at optimum and/or known levels. At each level of water availability, irrigation is scheduled to give the highest yield for the amount of water applied. The optimum depth of supplemental irrigation is influenced by the input-output price ratio as well as seasonal climatic conditions. The optimization analysis is used to identify the optimal depth of supplemental irrigation for given actual or anticipated input-output price conditions. The cost of irrigation water also plays a major role in optimization analysis. Sometimes farmers tend to overuse the irrigation water. In order to maximize the profit from supplemental irrigation, policies that will discourage the overuse of water should be implemented. This will balance profitability with resource sustainability (Oweis and Hachum 2009). The optimization analysis of supplemental irrigation considering all the concerning factors will help in achieving maximum profit with limited resources.

Supplemental irrigation helps farmer in managing the crop free from erratic and unpredictable rainfall. It extends support to small-scale farmers' livelihoods in three ways: (1) it improves yield, (2) it stabilizes production from year to year, and (3) it provides suitable conditions for the economic use of higher technology inputs. The supplemental irrigation from the harvested rainwater successfully counteracts the dry spells during the crop period and thereby reduces the risk of drought. Hence it has critical importance in the dryland and rainfed areas. Therefore, the potential of supplemental irrigation must be explored to enhance the agricultural water productivity to meet future food demand and growing competition for water (Kemeze 2020).

### 8.4.6 Increasing Land and Water Productivity by Adopting Supplemental Irrigation

Due to climate change, arid areas will experience less and more unpredictable rainfall. Lower rainfall will add to the moisture stress already experienced by dryland crops. Rainstorms of greater intensity are also expected to occur as a result of climate change. This will increase the runoff and soil erosion in rainfed areas, particularly on sloping soils. As more runoff flows downstream, the portion of rain that infiltrates the soil to promote plant growth will be reduced. Furthermore, the process of land deterioration is expected to accelerate. Supplemental irrigation in conjunction with water harvesting measures can provide viable solutions to this issue. Supplemental irrigation is the practice of applying required amounts of water to mostly rainfed crops when rainfall is insufficient to supply the necessary moisture for regular plant growth in order to increase and stabilize yield (Oweis and Hachum 2003). Supplemental irrigation, when used at critical crop growth stages, can result in significant increases in yield and water productivity while using a minimum amount of water. According to research conducted by the International Center for Agriculture Research in the Dry Areas (ICARDA), deficit supplemental irrigation should be used when there is insufficient water available for complete supplemental irrigation.

Ridge and furrow rain harvesting (RFRH) cultivation with 75 mm deficit irrigation as supplemental irrigation through border irrigation method gave significantly better yield than traditional flat planting with 150 mm irrigation for wheat cultivation. It resulted in considerably increased soil water storage, higher grain production (14.6%), and increased irrigation water productivity (57%) in comparison to flat planting with full irrigation (Ali et al. 2019). One strategy for minimizing drought damage, boosting water productivity, and improving the yield of dryland crops is to plan the timing of supplemental irrigation under limited water situations. Supplemental irrigation at flowering and grain filling ($I_4$) stages of canola and application of 1.5 mg/L of selenium increased the grain yield from 802 kg/ha plot without supplemental irrigation and selenium application to 2274 kg/ha, whereas highest water productivity (0.67 kg/m$^3$) was observed when 3 mg/L of selenium was applied along with $I_4$ treatment (Mohtashami et al. 2020). One supplemental irrigation at pre-sowing enhanced wheat grain output by 24.1% in the rainfed Shivalik Hills of Punjab (India) compared to no irrigation (Verma 2000). The use of supplemental irrigation via a drip irrigation system will result in more effective use of both water and nutrients. Yang et al. (2022) suggested replacing a part of nitrogen fertilizer with manure and providing supplemental irrigation as a carbon friendly and cleaner agronomic management strategy with high productivity in wheat cropping systems in the dryland of the Loess Plateau. Muluneh et al. (2017) analyzed the variation in maize yield between the current and projected $CO_2$ levels. Supplemental irrigation increased the maize output if used when the percentage of soil water depletion reaches 75% of the total amount of water available. Additionally, it was discovered that supplemental irrigation has only a minor impact in years with abundant rainfall but that utilizing 94–111 mm of supplemental irrigation in drought years can prevent complete crop failure. Cavalcante et al. (2022) examined the possibility of using brackish water for supplemental irrigation in maize under tropical dryland conditions. They found that the supplemental irrigation with brackish water increased the water productivity, reaching values that were 1.34, 1.91, and 3.03 times higher than the treatment without supplementary irrigation in the normal, drought, and severe drought conditions, respectively. The recent rainfall extremes and high-intensity rain episodes are anticipated to create substantial spatial and temporal variability in the quantity of surplus runoff available for harvesting; in some regions, it may even decrease. As a result, adequate planning and design of rainwater harvesting structures such as farm ponds, as well as effective exploitation of this stored water as supplemental irrigation via efficient water application systems such as drip, sprinklers, etc., are required.

## 8.5 Effect of Water Harvesting on Land and Water Productivity

### 8.5.1 Increasing Land and Water Productivity by Adopting Water Harvesting

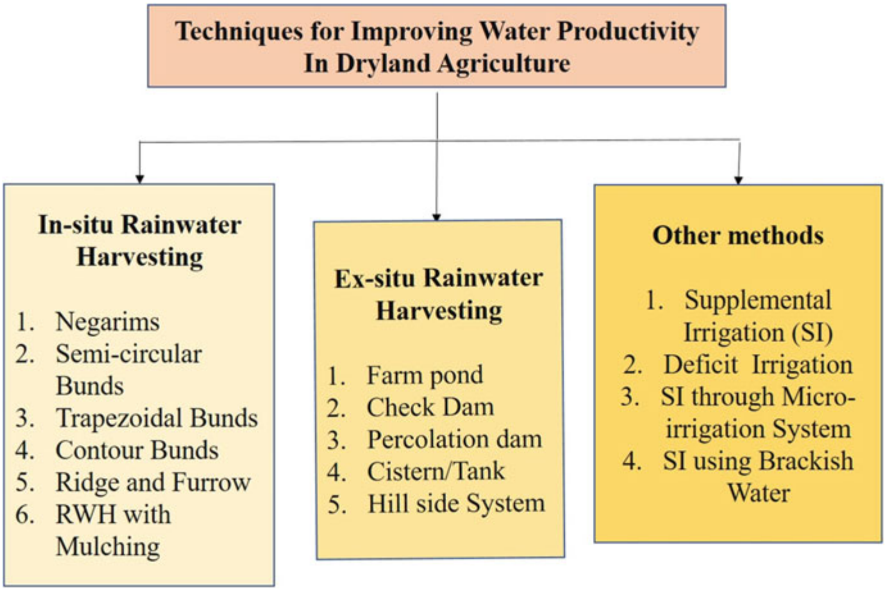
Water scarcity is a major contributor to low crop output and vulnerability in dryland agriculture systems. Rainwater harvesting (RWH) has long been seen as a sustainable method of enhancing the water productivity of dryland agriculture. When there is a significant amount of rainfall during a short period of time and the rest of the year is dry, the extra water can be stored in RWH structures and used for farming during the dry season. The irrigation provided from RWH techniques would save crops from the fatal damage due to water stress during critical dry spells. The crop, thus saved, will be able to absorb water from natural rain during rainy season. If the crop has not given irrigation during critical growth stages, it will be severely hampered, making any subsequent rain in the season useless. Hence, this method allows for more efficient agricultural production and increases water productivity by bringing the amount of water in the target region closer to the crop water requirements.

### 8.5.2 In-Situ Rainwater Harvesting

In situ RWH is a strategy that involves the use of technologies that improve the quantity of water retained in the soil profile by capturing or retaining the rain where it falls. The in situ RWH can reduce evaporation from the soil surface and surface runoff by changing the soil surface structure, the cover, and density of vegetation and by improving infiltration. This makes more water available in the root zone. Ridge and furrow rainfall harvesting (RFRH) system is an in situ RWH method that is often used in semiarid areas. Due to the recurrent droughts, the RFRH system has been utilized more frequently to increase crop productivity in dryland farming system. It involves making alternating furrows and ridges and covering the ridges with plastic film to collect rainwater (Li et al. 2020; Zhang et al. 2021). Besides, the collected rainwater is held near the crop root zone, which makes it easier for the plants to absorb water. This increases the efficiency in using rainwater. Wang et al. (2008) used RFRH system of rainwater harvesting system and observed that the tuber yield and water-use efficiency (WUE) trends were in line with the high moisture storage in which the tuber yield is increased by 158.6–175% in comparison to flat planting. The average WUE of RFRH system with plastic mulch also increased by 1.5–1.62 times. Wang et al. (2009) reported that the crop yield and WUE were higher with plastic-covered ridges than bare ridges in the RFRH system. They were also higher with gravel-and-sand-mulched or straw-mulched furrows than bare furrows in most situations. This was most likely brought on by plastic or mulch made of gravel and sand, which reduced evaporation. In most instances, the RFRH system with plastic-covered ridges and gravel-sand-mulched furrows achieved the maximum yield, and WUE for sweet sorghum and maize along with 30 mm of supplemental irrigation was used. Zhang et al. (2022) found that RFRH coupled with supplementary irrigation (RI) utilized 50% less irrigation water than border irrigation for wheat crop, but it optimized the spatial and temporal patterns of water consumption, boosting WUE and irrigation water-use efficiency (IWUE) by 1.1–17.6% and 86.5–109.2%, respectively. It also enhanced the grain yield by 3–6% while using 50% less irrigation water compared to border irrigation.

### 8.5.3 Ex-Situ Rainwater Harvesting

In ex situ RWH, runoff from a catchment area is diverted and stored in a natural or man-made reservoir so that it can be used for productive purposes such as drinking, irrigation, sanitation, etc. Ex situ RWH structures such as check dams, farm ponds, percolation tanks, etc. collect rainwater and surface runoff in order to act as surface storage and replenish groundwater. During periods of soil moisture stress, the stored water in these structures is used to satisfy the crop water requirements. Applying the stored water by traditional irrigation methods requires large amount of water, which could be improved by adopting better irrigation management strategies like micro-irrigation, deficit irrigation, etc. Mandal et al. (2020) demonstrated that adopting deficit irrigation strategy as supplemental irrigation from a check dam for groundnut crop could increase the crop productivity by 20% and can bring 140% more area under irrigation compared to full irrigation. When compared to a field that did not have access to the water from the farm pond, the increase in yield was approximately 51% for pigeon pea, 55% for chickpea, 36% for cotton, and 12.5% for soybeans on average (Kumar et al. 2016). Farmers from dryland area of Andhra Pradesh, India, have farm ponds recorded 31–32% higher groundnut yield compared to neighboring farmers without farm ponds due to application of life saving irrigation during prolonged dry spells (Chander et al. 2019). Farmers have been able to diversify their operations to include the cultivation of horticulture cash crops as well as the rearing of dairy animals as a result of RWH. High-value crops and high efficient irrigation application technologies like micro-irrigation and drip irrigation technologies are targeted, which will enhance the crop water productivity and water productivity of collected water can be maximized to its fullest potential.



## 8.6 Future Prospects and Conclusion

As the world grapples with climate change disaster, the extent of this problem is so severe that the future challenges in meeting the growing demands for water are beyond the capabilities of any country. Rainwater harvesting and supplemental irrigation are the need of hour to defend the water-scarce situation. The average rainfall of India is 118 cm according to Meteorological Department of India. Extreme precipitation regions: north-eastern regions and the windward side of the Western Ghats, experience an average of 400 cm of annual rainfall. Hence rainwater harvesting system should be the first line of defense against a water-scarce situation, and its future aspect should be explored.

However, the far-reaching initiatives related to rainwater harvesting implemented in Tamil Nadu, Karnataka, Maharashtra, Rajasthan, Andhra Pradesh, and Uttar Pradesh have converted 280 villages in these 6 states from "water-scarce" to "water-positive." The future dictates that easy retrofit, effective utilization of water storage space, elimination of fossil fuel driven pumping technology, and protection against flooding will be needed by rainwater harvesting system. Moreover, prototypes with reusable, recyclable characteristics capable of incorporating green space with water conservation should be trialed that could pave way for future water security. The current rainwater systems with characteristics of rainwater collection, filtration, extraction, clean pumping, green living energy efficient, and easy maintenance render much of the criteria expected from future system. However, acidification of rainwater in urban cities is playing major environmental issues. Hence it is required to modify the existing rainwater harvesting pit design so as to neutralize the pH of acidic rain, and the acidic rain need not to be flushed but can be used for recharge of groundwater (Verma and Sahu 2015). Apart from this different rainwater harvesting techniques should be tested for future rainfall data which can be predicted by different emission scenarios of climatic change for a specific period with calculation of future volumes of total runoff that can be harvested for different conditions under different scenarios (Zakaria et al. 2014).

Along with this an integrated research and development program can be designed for supplemental irrigation considering strengthening water user's organization, development of groundwater quality monitoring system, low-energy precision irrigation systems to manage water at scheme level, and development of simple and practical tools to support SI scheduling,

In water-scarce area, water is the vital resource instead of land to enhance agricultural production. Hence maximizing yield per unit water is the most viable objective in a scientometric water management strategy for dryland farming. Appropriate policies related to integrated approach of farmer's participation and water cost recovery are needed to galvanize adaptation of improved management options (Prinz 1996). Supplemental irrigation is the key solution for water-scarce situation rather than full irrigation in dryland area as it is very much potent to increase water productivity. Therefore, to support its operation, inputs and cultural practices must be optimized. Strengthening of community participation must be needed for wide adaptation and implementation of improved and modern water saving technologies to address climate change impacts in dryland farming.

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# Assessment and Management of Soil and Water Erosion in Dryland Ecosystem

9

Gayatri Sahu and Samanyita Mohanty

## Abstract

Dryland ecosystems manifest a significant part of the earth system in terms of total area, production and socioeconomic and ecological importance. They exhibit immense diversity with reference to climate, topography, geology and soil and groundwater resources which makes them an unexplored area. The concern over dryland ecosystem in future generation is intensifying due to continuous growth in human population, inadequate land-use practices and deviation both in global and regional climate. Lately, drylands are being considered as isolated ecosystems with low production potential, subjected to desertification or land degradation. Wind erosion dominates the soil degradation process in drylands, closely followed by water erosion and chemical degradation, while physical soil degradation is of least importance in drylands. Soil degradation creates huge havoc attributing to the depletion of soil organic carbon and nutrient pools, denudation of vegetation cover, reduction in net primary productivity, increase in frequency and intensity of droughts (especially pedological and ecological droughts) and loss of ecosystem resilience. The critical drivers of dryland environments lead to a degraded condition of primary production. Building an integrated approach to overcome sustainability issues in the dryland areas is the need of the hour. The concept of sustainable land management (SLM) is widely being promoted in response to land degradation and desertification in these areas. SLM prioritizes the utilization of land resources (soils, water, plants and animals) to produce goods and services that meet the growing demand of human population while, assuring the long-term productive potential of these

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resources. It represents the basic building block for sustainable agricultural development based on the objectives of productivity, resilience, protection, practicability and acceptability. There is an urgent need to upgrade the ability of the land users through education and extension as well as improve access to financial and social capital to manifest the SLM adoption. Proper adoption of SLM practices is critical for protecting the soil and other natural resources besides maintaining several ecosystem services that are essential for human well-being.

**Keywords**

Dryland ecosystem · Sustainable land management · Natural resources · Environment

## 9.1 Introduction

The drylands of the world are indispensable for crop production and encompass a diverse array of ecosystems, viz. deserts, steppe, savannas, chaparral, grasslands and rangelands, yet all being distinguished by scarcity of water. They exhibit immense diversity in terms of climatic conditions, landscapes, soils, geological substrata and surface and groundwater resources. Albeit, drylands constitute the fragile ecosystems which are highly sensitive to degradation, it is not always easy to differentiate the natural occurring processes from human-induced degradation trends that are related to its dryness (De Pauw 2010).

Drylands are a critical part of the earth system in terms of total area, production and socioeconomic and ecological importance. It forms the largest biome complex on earth, occupying approximately 41% of the terrestrial land surfaces (Maestre et al. 2012) and accounts for about 40% of the global net primary productivity (Wang et al. 2012). It is estimated that more than 2 billion people (i.e. 38% of the total world population) inhabit in dryland regions (United Nations Development Programme (UNDP 2014; Pravalie 2016), and 90% of this population live in developing countries (United Nations Environment Programme 2007; Armah et al. 2010). The dryland ecosystem expands to about 6.1 billion hectares, with a spectrum of climate conditions ranging from hyper arid deserts, where the annual evapotranspiration is more than 20 times the annual precipitation, to dry subhumid grasslands and forests, where the annual evapotranspiration is as low as two to three times the annual precipitation (Trees FAO 2019). Finally, drylands serve as an important source of cultural identity and diversity, as well as landscapes for recreation and tourism (Safriel and Adeel 2005).

Dryland ecosystems remain an area less explored as they are (1) structurally and functionally dynamic in nature due to intermittent and unpredictable water availability and (2) marginalized by long-term, continuous field measurements that are transformed into larger, easily accessible networks (Biederman et al. 2017). The concern over dryland ecosystem in future generation is intensifying by continuous expansion of human population, inadequate land-use practices and deviation in global and regional climate (Li and Zhao 2012). Drylands are predicted to expand by 10–23% by the end of the twenty-first century and climatic variation in these regions escalate the challenging issues of food security, human welfare, environmental quality and water supply (Ravi et al. 2010; Asseng and Pannell 2013; Zinyengere et al. 2014).

An integrated approach, which combines participatory research and technology development to locally defined problems and management goals, is vital for the sustainable management of dryland ecosystems. Therefore, a proper understanding to speculate the influence of climate change on dryland areas and global sustainability is critical (Verstraete et al. 2009; Qi et al. 2012).

## 9.2 Land Degradation in Dryland Ecosystems

Drylands are considered as isolated ecosystems with low production potential, subject to desertification or land degradation. According to land degradation assessment in drylands (LADA) project report, land degradation is defined as the reduction in the capacity of the land to provide ecosystem goods and services, over a period of time, for its beneficiaries (Biancalani et al. 2011). Desertification and land degradation are used synonymously, and the difference between them is not process-based but geographic in nature. Although, land degradation can occur anywhere across the world, but when it occurs in drylands, it is considered as desertification. Worldwide, land degradation affects about 1.5 billion people; out of these 250 million people reside in drylands, and about 1 billion people in over 100 countries are at risk (Reynolds et al. 2007; Lean 2009; United Nations Convention to Combat Desertification 2014).

Drylands are highly prone to degradation, and its consequences affect ~250 million people in the developing world (Reynolds et al. 2007). The principal processes of land degradation include erosion by water and wind, chemical degradation (viz. acidification, salinization, fertility depletion and decrease in cation retention capacity), physical degradation (viz. crusting, compaction, hard-setting, etc.) and biological degradation (viz. reduction in total and biomass carbon and decline in land biodiversity) (Sivakumar 2007). Dryland ecosystems with low rainfall, long dry seasons, recurrent droughts, mobile surface deposits, skeletal soils and sparse vegetation cover are mostly vulnerable to degradation (Dregne 1983; Le Houérou 1986; Kassas 1995). According to the Global Assessment of Soil Degradation (GLASOD) map (Oldeman 1994), wind erosion is the most significant soil degradation process on drylands, closely followed by water erosion. Chemical degradation is the third soil degradation process, and physical soil degradation is of least importance in drylands.

Globally, water is the major agency of soil erosion, but in arid and semiarid areas, wind erosion can be substantial and even the dominant agent of soil erosion (Ravi et al. 2010; Belnap et al. 2011) or desertification (Brown and Nickling 2003). Degradation of soil and vegetation can result to about 70% reduction in ecosystem functions in drylands (Dregne and Chou 1992). Soil degradation creates huge havoc attributing to the emission of radiatively active gases, depletion of soil organic carbon and nutrient pools, denudation of vegetation cover, reduction in net primary productivity, increase in frequency and intensity of droughts (especially pedological and ecological droughts) and loss of ecosystem resilience. Low fertility of dryland soils is extremely vulnerable to various climate and human-induced degradation (Maestre et al. 2013; Li et al. 2016; Zhou et al. 2016). Climatic anomalies in drylands strongly influence the economy and society of developing countries (Huang et al. 2017; Fu and Mao 2017).

## 9.3 Drivers of Land Degradation and its Consequences

The critical drivers of dryland environments lead to a degraded condition of primary production. A measurement of this indicator under drylands is the degree of “land degradation” or “desertification”. Land degradation is caused by both natural and anthropogenic direct drivers, which are in turn moulded by certain indirect drivers. Land degradation can arise either of inherent natural phenomenon or by extreme situations. However, these events are exacerbated by anthropogenic actions, as in the case of landslides that result from construction of roads or pest outbreaks that develop due to the introduction of these new habitats by humans. The influence of natural drivers is also intensified by human-induced climate change.

Globally, the most widespread drivers of land degradation are those that are directly related to human interferences. Indirect drivers are the ultimate underlying causes of land degradation, as they arise from the basic functioning of the ecosystem. Fluctuations in temperature, wildfires, flooding, landslides and dust storms are also among the natural events that are both a cause and an effect of degradation. While traditional agricultural approaches are no longer capable to meet the burgeoning population, they are also being replaced by other damaging agricultural alternatives.

### 9.3.1 Direct Drivers

Direct drivers have an explicit influence on the structure, function and composition of dryland ecosystems. Direct natural drivers are beyond the human control and are not attained by human activities (e.g. climate change, landslides, tectonic activity), whereas human-induced or anthropogenic direct drivers can be conceptualized as the set of activities performed by humans that results in degradation and restoration processes, such as land-use and land management activities (e.g. land clearance, introduction of invasive species, fire suppression, etc.).

#### 9.3.1.1 Soil Erosion

Soil erosion is defined as the detachment and transport of soil particles and its subsequent redeposition mainly by the action of wind and water. Soil erosion is a natural land surface process, which can be exacerbated by anthropogenic and biophysical factors creating problems for human sustainability (Lal 2015a, b). Soil erosion is often considered as a cause and an effect of desertification (Nicholson et al. 1998; Lal 2001; Millennium Ecosystem Assessment 2005). The different processes of soil erosion modify the physicochemical and biological properties of soil, which results in reduction of agricultural productivity and cultivable land area thereby facing the problem of food scarcity, especially in the context of increasing world population (Graves et al. 2015). Soil loss from agricultural land leads to the decreased crop production, potential damaged drainage networks and lower water quality surface (Issaka and Ashraf 2017; Prasad et al. 2014). Soil erosion adversely affects agricultural productivity, water quality, hydrological system, soil fertility and environment (Lal 2015a, b). Increasing rate of soil erosion due to climatic variation increases the aridity index which results in enhanced loss of soil resources and biodiversity. This further escalates the rates of soil erosion and results in loss of vital ecosystem services from drylands, including reduction in primary production and carbon sequestration (Chapin III et al. 1997).

Soil erosion affects the productivity and spatial arrangement of dryland vegetation and soil resources (Schlesinger et al. 1990; Puigdefabregas 2005) and is recognized as a possible threat to sustainable agricultural production in arid and semiarid landscapes (Lal 2001). In agricultural crop lands, accelerated soil erosion incurs loss of fertile topsoil, depletion of soil fertility and subsequent decrease in crop productivity (Lal 2001; Lal et al. 2003; Li et al. 2008). The detachment, transport and deposition of fine soil, which holds most of the nutrients, affect the soil organic carbon pool and thus influence the global carbon budget (Lal et al. 2003; Li et al. 2008). Thus, erosion concludes with reduction of soil nutrients and the capacity of soil to hold water and causes an overall decrease in the ability of land to sustain vegetation. Furthermore, these erosion processes result in the movement of sediments and various agricultural pollutants into the water bodies, thereby affecting the scarce fresh water resources present in these dryland ecosystems (Lal 2001).

The phenomenon of soil erosion depends on soil erodibility, climatic erosivity as well as land and crop management practices. Climate change can influence all of these parameters and greatly accentuate the erosion hazard. Increase in frequency and intensity of extreme weather events can enhance the rainfall intensity and its kinetic energy, wind velocity and its erosivity and run-off velocity and its shearing and sediment carrying capacity. Thus, the progressive soil erosion of the dryland tropics may reduce the already low amount of SOC stored in these soils. Decline in SOC pool and soil aggregation, combined with increase in land conversion for meeting the increasing human demands, may severely accelerate soil erosion and desertification hazard. Wind erosion hazard, one of the major degradation processes in drylands, can also be increased because of the dynamic climate change in arid regions.

#### 9.3.1.2 Climate Change

The relatively low productivity and low soil moisture content of drylands are often exacerbated by the unimodal pattern of rainfall, resulting in a long period during which soil moisture falls. Low and infrequent precipitation patterns and radiation-induced evaporation jointly and directly drive a linear sequence of biophysical processes.

Climatic conditions both lead to and exacerbate land degradation in dryland ecosystems. Drylands are considered hotspots of climate change, with increasing temperatures, variable precipitation and an increase in extreme events (Huang et al. 2017). Over the past few decades, the greatest temperature increase in worldwide has been observed under drylands, because surface warming in drylands is approximately 20–40% higher than humid lands (Huang et al. 2017). Apart from variation in mean precipitation, increase in precipitation variability, shift in precipitation seasonality and increase in the frequency and magnitude of drought are projected to occur in drylands (IPCC 2014; Sloat et al. 2018). The combined effects of increasing temperatures and altered precipitation are likely to reduce the quantity of water availability. Climate change shapes the extent, severity and frequency of occurrence of other degradation drivers, which in turn influences potential future climate.

Besides changes in temperature and precipitation, there has also been an increase in the frequency and intensity of extreme events, including heavy rainfall events and temperature extremes in many regions over the last several decades, and these are further projected to rise in the coming decades. Dust storms can erode top soil, damage crops and infrastructure, reduce air quality and even disrupt transport networks. Similarly, severe droughts can lower crop productivity; reduce water availability for humans, livestock and wildlife; lead to the loss of biodiversity; depress plant performance and survival even in arid and semiarid systems; and thus make forests more susceptible to degradation.

#### 9.3.1.3 Land-Use Change

Most of the land area used for livestock production (i.e. rangelands) occurs under dryland ecosystem (Sayre et al. 2017). The development of unsustainable livestock production systems has resulted in shifts in plant functional types worldwide (Bestelmeyer et al. 2018; Jamsranjav et al. 2018). Recent disruptions in pastoral governance systems and current increase in livestock numbers are causing significant change in the state (Todd and Hoffman 2009; Basupi et al. 2017; Fernández-Giménez et al. 2017). As major parts of the drylands are relatively unproductive for cropland agriculture (when compared with humid environments), they have escaped the process of widespread conversion from rangeland or wildland uses to cropland (Ramankutty and Foley 1999).

Recent changes in climatic, economic and technological drivers have accelerated the conversion of land to drylands. Urbanization in rangelands also continues to occur (Bestelmeyer et al. 2015; Allington et al. 2017) which is associated with energy development and mining (Sternberg and Chatty 2016; Copeland et al. 2017). Land conversion in drylands may have several ecological, economic and societal effects, viz. fragmentation with respect to rangeland management operations (e.g. use of fire) and effects on wildlife and air quality (Sacchi et al. 2017).

## 9.3.2 Indirect Drivers

The greatest threat to future climate change arises, perhaps not from its role as a direct driver of degradation but rather from its ability to act as a threat multiplier for other degradation drivers, both by exacerbating the effects of other land degradation drivers, as well as by altering the frequency, intensity, extent and timing of events, such as fires, pest and pathogen outbreaks. The indirect human-induced drivers of change in drylands are heterogenous in nature and act on several levels which includes demographic drivers (viz. local population growth or immigration resulting from regional population growth), economic drivers (viz. local and global market trends) and sociopolitical drivers (viz. local and regional land policies as well as scientific and technological innovations). According to the desertification paradigm, these combined drivers impart significant pressure on drylands in anticipation of increased provision of ecosystem services.

### 9.3.2.1 Intensive Agriculture

Intensive and conventional agriculture have resulted in widespread clearance of land for mechanized farming under monocultures, the removal of trees and evacuation of traditional crop rotations and other sustainable land management practices. Drylands cultivated with the above conditions rapidly diminish soil biodiversity – fungi, bacteria and other beneficial organisms which are important for nutrient and organic carbon recycling and turnover in the soil.

### 9.3.2.2 Salinity Hazard

Increased salinity is caused by land clearing, mainly for agricultural production, and this situation occurs when the water table rises and brings natural salts to the soil surface. The major factor contributing to this hazard can be employed to the farming practices that incorporate shallow-rooted crops and pastures into the system. Mismanagement of groundwater resources, in addition to increased evaporation rates and reduced precipitation rates, has positively contributed to soil and water salinization in several countries.

### 9.3.2.3 Ineffective Planning and Governance Policies

Lack of multisectoral planning around natural resources has been a huge issue. Conditions with isolated sectoral planning lead to emergence of negative externalities with the interaction of one sector policy negatively affecting the outcome of another sector policy. Another important driver of land degradation is fragmented land holdings and ineffective governance over natural resources, particularly in areas like grasslands and dry forests. Millions of emigrated people have been forced to abandon their respective land holdings, which has led to a contraction in supply through a breakdown in production, the destruction of physical capital, and the discontinuity of labour, thus deteriorating both the land and economy.

## 9.4 Sustainable Land Management Strategies

In the present generation, the concept of sustainable land management (SLM) is gaining immense priority and is widely being promoted in response to land degradation and desertification. It entails various land and water conservation technologies that assist the production system and environment for current as well as future generations. In a nutshell, SLM can be defined as the utilization of land resources (soils, water, plants and animals) to produce goods and services that meet the growing human needs on one hand, while assuring the long-term productive potential of these resources and maintenance of their environmental functions, simultaneously on the other hand (WOCAT 2007).

Recent efforts have been made to scale up the local sustainable land-use practices and initiatives which may eventually get modified into large-scale integrated multi-stakeholder assessments to reconstruct land degradation through SLM (Reed et al. 2015), with a focus on knowledge reciprocation and learning-based participatory approach (Bautista et al. 2017) to build resilience so as to sustain principal ecosystem services in dryland socio-ecological systems (Biggs et al. 2015). This approach can assemble together under rapidly changing environmental socioeconomic and political conditions.

Sustainable management of land resources is the basic building block for sustainable agricultural development. It amalgamates the technologies, policies and activities which aims at integrating the socioeconomic principles along with environmental complications, simultaneously so as to:

1. Maintain and boost the productivity
   Preserve the natural resources and prevent soil and water degradation.
   Reduce the production risk and intensify the stability of soil against various degradation processes.
2. Be economically feasible
3. Be socially acceptable

These are the pillars of sustainable land management and are entitled as the basic foundation on which sustainable land management is being developed. The monitoring and evaluation of the sustainability issues need to be based on the objectives, i.e. productivity, resilience, protection, practicable and acceptable (Smyth and Dumanski 1993). These pillars were deduced to provide useful guidance to assess sustainability of a particular system.

There is no such particular definition for SLM. Still, it can be defined as a research model which must include a goal/objective statement, a conceptual framework, a set of protocols and several indicators for diagnosis (Gallopin 1996). The major objective of such research model is to evaluate the influence of uncertain events, but the process of evaluation is defined by scientific protocols. The model/technology can be an agronomic, structural or organizational measurement applied in the field level. An SLM approach can be defined as the measure that is used to promote and implement a specific SLM technology, whether through a project, an indigenous system or as a community initiative. Although the objectives of SLM have been constructed and are being implemented to a satisfactory extent, there are certain challenges faced by SLM particularly in drylands areas. These include low productivity, climate anomalies, water stress and high risks of natural hazards, population pressure and their migration.

To ensure the success rate of SLM, three approaches are being used to assess the extent of SLM adoption. Firstly, a logistic regression model is used to estimate the probability of adoption of SLM technologies, a Poisson regression model to measure the number of SLM technologies being adopted and, lastly, a multivariate probit model to estimate the simultaneous adoption of different SLM technologies. The adoption activity and the number of SLM technologies already being validated is determined by a sequence of elements, i.e. biophysical, socioeconomic, demographic and plot characteristics. The crucial biophysical factors influencing the adoption of SLM practices include rainfall, temperature, topography and the agroecological characteristics. The significant function of rainfall and agroecological classification on number of SLM technologies adopted necessitate for proper geographical planning and targeting of the SLM practices by stakeholders and policymakers. The relevant demographic and socioeconomic factors include age and education level of the family head, family size, land holding size, credit cooperatives, access to credit facilities and proximity to market services. Obtaining the land tenure for prolonged period and getting access to relevant agricultural information pertaining to SLM will play an important role in enhancing the adoption rate and number of SLM adopted. The investment effort into SLM practices is worthwhile both in the short and long run.

## 9.5 Conclusion

Management of land in sustainable manner is a massive challenge for land users and other stakeholders around the world. Land degradation in dryland ecosystems is presently becoming a highlighted issue due to the increasing number of causes and its effects. Drylands are characterized by climatic variabilities and water stress which makes it difficult to reap benefits from it without affecting the existing resources. With proper policies and adequate support, the drylands can be productive, and the livelihoods of dryland communities can be significantly upgraded with benefits to the global development agenda with respect to poverty alleviation, land degradation mitigation and climate change stabilization. Building an integrated approach to overcome sustainability issues in the dryland areas is the need of the hour. There is an urgent need to upgrade the ability of the land users through education and extension as well as improve access to financial and social capital to manifest the SLM adoption. Local institutions providing credit services and input facilities such as seed and fertilizers and extension services should be given prior importance for formulating several development policies. The assessment phase of SLM technologies adoption revealed that most of these technologies were complementary to each other – such as the use of improved seeds, organic amendments and synthetic fertilizers. Therefore, proper adoption of SLM practices is critical for protecting soil and other natural resources besides maintaining several ecosystem services that are essential for human well-being.

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# Advances in Micro-Irrigation Practices for Improving Water Use Efficiency in Dryland Agriculture

# 10

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## Abstract

Agriculture sector is one of the most water demanding sectors followed by the domestic, industrial, and power sectors. Globally India uses highest amount of freshwater; moreover, the country's total water use is greater than any other continent. Despite of this fact food security is low because of several constraints such as institutional and technical. Technical constraints highly relate to absolute water scarcity and failure of crops to efficient water utilization. Globally 41% of the terrestrial area is found to be under dryland cover and approx. 20 million people depend on it for agricultural activities. Drylands combined with water issues and diversity, therefore, require appropriate practices and strategies to mitigate the adverse environmental effect on agriculture. Efficient water utilization could be an effective strategy in drylands to cope with the water scarcity. The water use efficiency (WUE) can be achieved through advance practices such as crop residue management, mulching, row spacing, and micro-irrigation. At field level advanced technology reduces the soil water evaporation and conserves more water for crop utilization. Climate change also affects plant growth; however, the enhanced WUE through crop selection, cultural practices, and advance micro-irrigation technologies could be adopted to offset the impact of a changing

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climate. Micro-irrigation (MI) method (drip and sprinkler) is a solution that reduces losses (conveyance and distribution) and allows higher WUE. This book chapter highlights the major advancement in micro-irrigation practices and its significance in improving WUE in dryland agriculture.

**Keywords**

Arid agriculture · Climate change · Drip irrigation · Irrigation efficiency

## 10.1 Introduction

The difficulty to access water has become one of the fundamental issues globally through the twenty-first century (Gleeson et al. 2012; Elbeltagi et al. 2021). Most of the readily available fresh water on the earth's surface is used up by the agricultural sector. The amount of water withdrawn from the surface of the earth in developing countries is estimated as 81%, while the same is 71% globally. Furthermore, irrigation plays a major role in the consumption of not less than 55% of the world's freshwater reserves (Amarasinghe and Smakhtin 2014; Kushwaha et al. 2021). Being able to provide food for the world's population has become a conundrum amidst freshwater scarcity (Fischer et al. 2007; Vishwakarma et al. 2022). Heightened demand for the limited water resources under rising climate change impacts, and certain agricultural commodities have constantly hinted upon the need for ways to devise efficient use of the existing water resources at our fingertips. This will also require smart distribution of limited water resources in terms of appropriate time and through the right channel toward premium food production (Kushwaha et al. 2016; Dhillon et al. 2019).

The dryland regions are dominated by grazing and rainfed cropping because of water scarcity, and the crop production is usually low in the region. There are two major problems of water scarcity due to meteorological drought and the inability of plants to use soil water under drought condition (Stroosnijder et al. 2012).There are various methods to cope with this kind of drought such as furrow-diking, drip irrigation, sprinkle irrigation, deficit irrigation, etc. (Araya and Stroosnijder 2010; Stroosnijder et al. 2012). The concept of water use efficiency (WUE) is introduced by Briggs and Shantz (1913) and is defined as the ratio of plant productivity and water applied. Climate change because of increased carbon dioxide level and temperature, erratic variation in rainfall, and humidity affects the water use by plants (Kushwaha et al. 2022). These changes have increased the limitation of use of soil water availability because of more variation in rainfall during crop-growing span and soils having low water holding capacity (Hatfield and Dold 2019). Xiao et al. (2013) Analyzed and observed spatial patterns in the water and carbon flux because of changes in the temperature, rainfall, and crop-growing season, and they have compared these fluxes across latitudes in the eddy covariance flux system. They conclude that WUE of various ecosystems depends on annual rainfall, gross primary productivity, and crop-growing span.

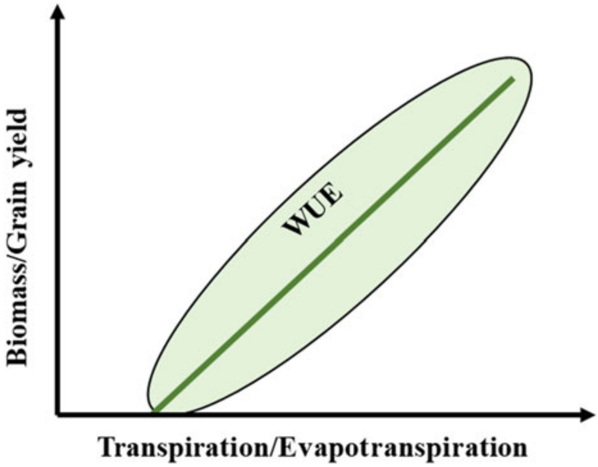


**Fig. 10.1** Graphical representation of the relationship between WUE, crop water use and bio mass or grain yield

WUE plays an important role in the agricultural production especially in the semiarid and dry land regions, because of the increasing irrigated area and high water requirement of crops (Bhattacharya 2019). The crop productivity could be improved without change in water use rate and resulted increased WUE (Basso and Ritchie 2018), but the prevailing hypothesis for WUE is that the crop productivity increases with increase in the water use (Fig. 10.1). In order to improve WUE, the increase in crop water use will require (Hatfield and Dold 2019). The crop water used can be improved through adoption of irrigation scheduling, timing, and critical and advance micro-irrigation techniques by the farming communities (Araya and Stroosnijder 2010; Bhattacharya 2019). The main advantage of advanced micro-irrigation techniques is that these methods are helping in reduction of soil water evaporation from the space between two rows during early season and improve water use by the crop.

This chapter will discuss in details the advanced techniques and strategies for improving water use efficiency and enhancing sustainable use of available water management at regional level as well as global scale. The present status of irrigation techniques, potential, challenges, and major points with the recommendations has been presented.

## 10.2 Status of Micro-Irrigation in India and at a Global Scale

### 10.2.1 Global Scenario of Sprinkler and Micro-Irrigation

Irrigation technologies like sprinkler and micro-irrigation are generally referred to as the pressurized system. Micro-irrigation term represents the irrigation through drippers, micro-sprinklers, bubblers, microjets and sprayers, and drip tapes. The history shows sprinklers are known for more than eight decades, and wide applicability for irrigation in agriculture field begun in early 1950s (Keller 2002) and had covered over 21.6 million hectare (Mha) area globally under sprinkler irrigation by late 1990s (Indian National Committee on Irrigation and Drainage 1998). In case of drip irrigation (micro-irrigation), wide applicability commenced in 1970s in some part of world, for example, Israel, South Africa, Mexico, Australia, the USA, and New Zealand, for wide spaced vegetables and horticultural crops. At the beginning coverage under micro-irrigation (drip) was found to be around 0.056 Mha area only. However, slow but steady growth of about 0.41, 1.77, and 3.0 Mha in 1981, 1991, and 2000 was reported, respectively (ICID 1993; Reinders 2000).

The survey on micro-irrigation at global scale (for about 35 countries) was done a long ago in 1991 by National Committees of International Commission on Irrigation and Drainage (ICID-NC), but no further official survey was conducted. However, from the 1990s the micro-irrigation coverage reached approx. Double in the last one and a half decade. The data from various sources mainly ICID-NC, FAO-AQUASTAT and other official publication for different years was collected and reported for development of sprinkler and micro-irrigation at world scale (77 countries).

Availability of actual/precise data on continuous basis (yearly) is difficult due to temporal fluctuation of coverage of irrigated area at country level and so to global scale. The nonavailability of reported data on pressurized (sprinkler and micro) irrigation in many countries limits the actual representation of micro-irrigation statistics at global scale. Different worldwide surveys or reporting deliver different statistics based on their plan of work, area considered, data availability, and other suitability of work. International Commission on Irrigation and Drainage (ICID) compiles the word data reports through its member countries and other sources. ICID conducted survey in 1991 with consideration of 35 countries as per data availability. Statistics from FAO (FAO 2003a, b) was found to be reported 276 Mha area as irrigated worldwide form 174 countries in 2003. In this chapter data for sprinkler and micro-irrigation coverage at world level is compiled from ICDI-NC 2018 and other official publication. The recent available data from ICDI-NC 2018 shows the total of 218.43 Mha area under irrigation (of which 75.19 percent under drip and sprinkler) from 46 countries (Fig. 10.2). The top 20 countries on basis of total irrigated data are represented in Fig. 10.2 through bar graph and all 46 countries through world map (size corresponding to amount of total irrigated area of country and color corresponding to percent of total irrigated area under micro-irrigation).

### 10.2.2 Indian Scenario of Sprinkler and Micro-Irrigation

India leads the world with net irrigated area of approx. 68.8 Mha. India has potential to irrigate 139 Mha area. Till 2005 only, the area under sprinkler irrigation in India has rose to 1.63 million ha (Kulkarni 2005) from 0.23 Mha in 1985 (Naidu and Singh 2004). Similarly for drip irrigated area, only 1000 ha was reported in 1985 which increased to 35,000 ha, 152,930 ha, 350,850 ha, and 500,000 ha in 1990, 1995, 2000, and 2005, respectively. Indian government has estimated an ultimate potential

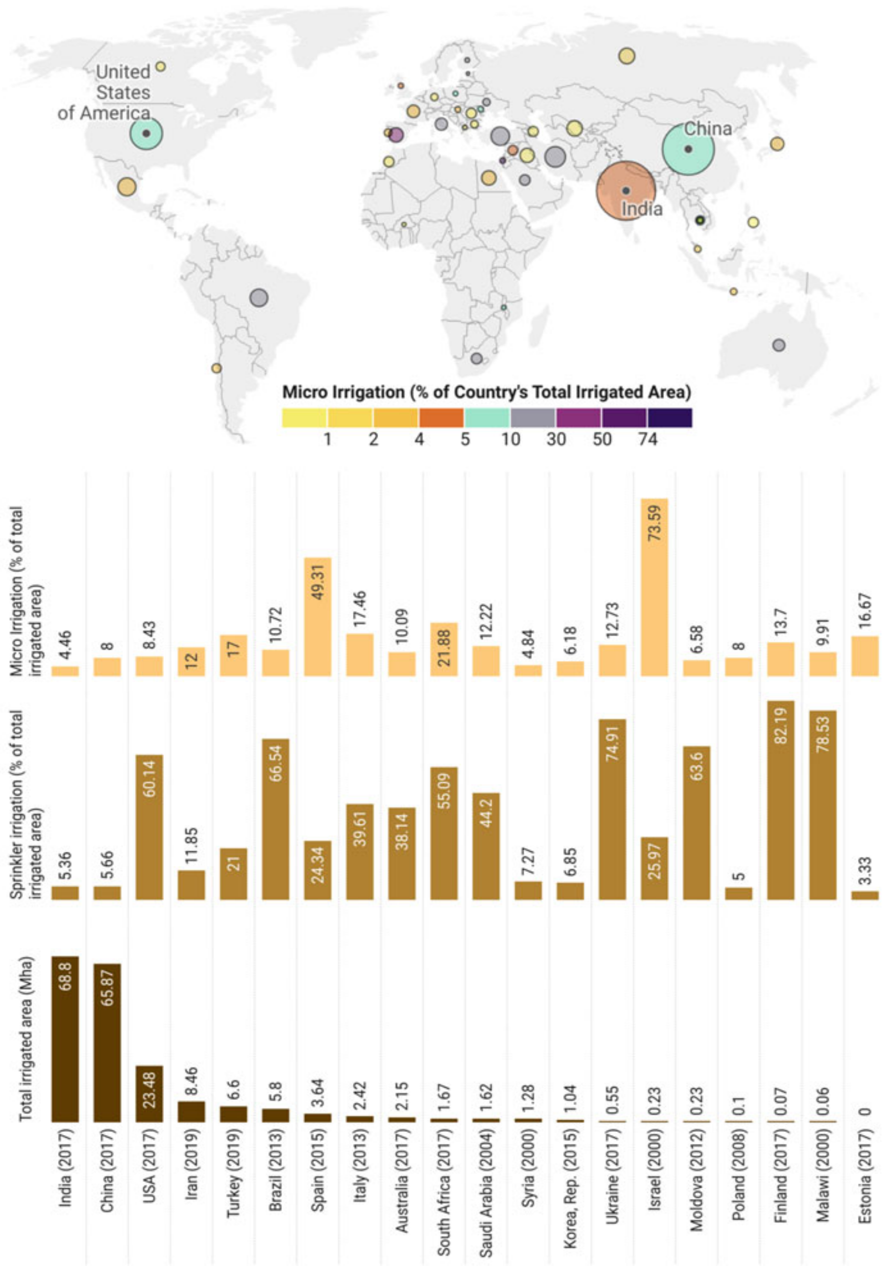
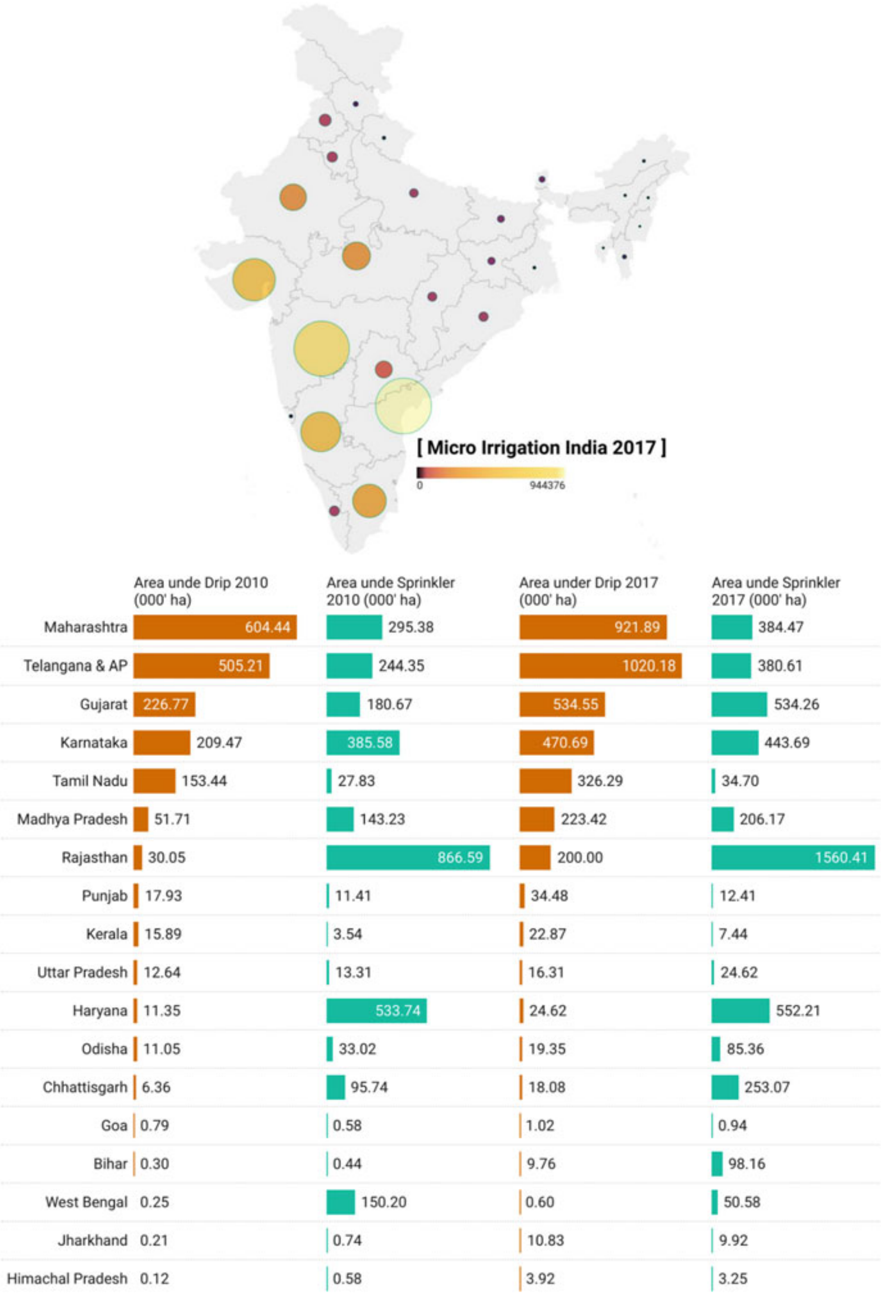


**Fig. 10.2** Sprinkler and micro-irrigation development at global scale

area of 27 and 42.5 Mha for micro and sprinkler irrigation, respectively (Naidu and Singh 2004). During 2017, 3.87 Mha area under drip and 4.65 Mha area under sprinkler irrigation was reported (data.gov.in). However, this adoption is far below than potential estimated. Figure 10.3 represent the Indian scenario of sprinkler and micro-irrigation. Bar graph is representing the leading states of India in drip and sprinkler irrigation also the comparison from 2010 to 2017 (Fig. 10.3). Indian map in Fig. 10.3 gives the spatial representation for area reported under drip irrigation in 2017 (data.gov.in). Top five states being Maharashtra, Andhra Pradesh & Telangana, Karnataka and Gujarat contribute more than 80% of total area covered by drip irrigation whereas Rajasthan and Hariyana leads with sprinkler irrigated area in country. Indian farmers mainly adopted drip technology for horticultural crops (banana, grapes, mango, pomegranate etc.) and sprinkler technology for field crops (wheat, pea, sorghum, mustard etc.).

### 10.2.3 Timeline of Micro-Irrigation Development in India

India stated the journey a log back in 1992 with Centrally Sponsored Scheme (CSS) on Use of Plastic in Agriculture in direction to safe and valuable utilization of plastic made technologies in agriculture.Through fundings from various departments of Indian Gov. funds like Rural Infrastructure Development Fund and Accelerated Irrigation Benefit Programme (AIBP) were started in 1995 and 1996 respectively in this direction. Further, grater trust was developed by programs like Integrated scheme of oilseeds, pulses, oil-palm and maize (ISOPOM) in 2004, National Horticulture Mission (NHM) in 2005 etc. and emphasized the application requirement of developed irrigation technologies. Hence, the dedicated and focused programs were started by centra government, as in 2006, on Micro-irrigation (CSS-MI) under CSS and in 2007 Rastriya Krishi Vikas Yojana (RKVY) under National Food Security Mission. In 2010 the CSS was improved, restructured and declared as National mission on Micro-irrigation (NMMI) and subsequently covered by National Mission on Sustainable Agriculture (NMSA) in 2014. Finally, in 2015 all these were covered and brought under a single scheme Pradhan Mantri Krishi SinchayeeYojna (PMKSY) with financial assistance to farmers as form of subsidy in investment on micro-irrigation setup from union budget in conjunction with state share. The historic schemes from Indian government in field of agriculture, particularly in irrigation sector, with their time of implementation are illustrated in Fig. 10.4.



| | Area unde Drip 2010 (000' ha) | Area unde Sprinkler 2010 (000' ha) | Area under Drip 2017 (000' ha) | Area unde Sprinkler 2017 (000' ha) |
|---|---|---|---|---|
| Maharashtra | 604.44 | 295.38 | 921.89 | 384.47 |
| Telangana & AP | 505.21 | 244.35 | 1020.18 | 380.61 |
| Gujarat | 226.77 | 180.67 | 534.55 | 534.26 |
| Karnataka | 209.47 | 385.58 | 470.69 | 443.69 |
| Tamil Nadu | 153.44 | 27.83 | 326.29 | 34.70 |
| Madhya Pradesh | 51.71 | 143.23 | 223.42 | 206.17 |
| Rajasthan | 30.05 | 866.59 | 200.00 | 1560.41 |
| Punjab | 17.93 | 11.41 | 34.48 | 12.41 |
| Kerala | 15.89 | 3.54 | 22.87 | 7.44 |
| Uttar Pradesh | 12.64 | 13.31 | 16.31 | 24.62 |
| Haryana | 11.35 | 533.74 | 24.62 | 552.21 |
| Odisha | 11.05 | 33.02 | 19.35 | 85.36 |
| Chhattisgarh | 6.36 | 95.74 | 18.08 | 253.07 |
| Goa | 0.79 | 0.58 | 1.02 | 0.94 |
| Bihar | 0.30 | 0.44 | 9.76 | 98.16 |
| West Bengal | 0.25 | 150.20 | 0.60 | 50.58 |
| Jharkhand | 0.21 | 0.74 | 10.83 | 9.92 |
| Himachal Pradesh | 0.12 | 0.58 | 3.92 | 3.25 |

**Fig. 10.3** Sprinkler and micro-irrigation development in India during 2010 and 2017

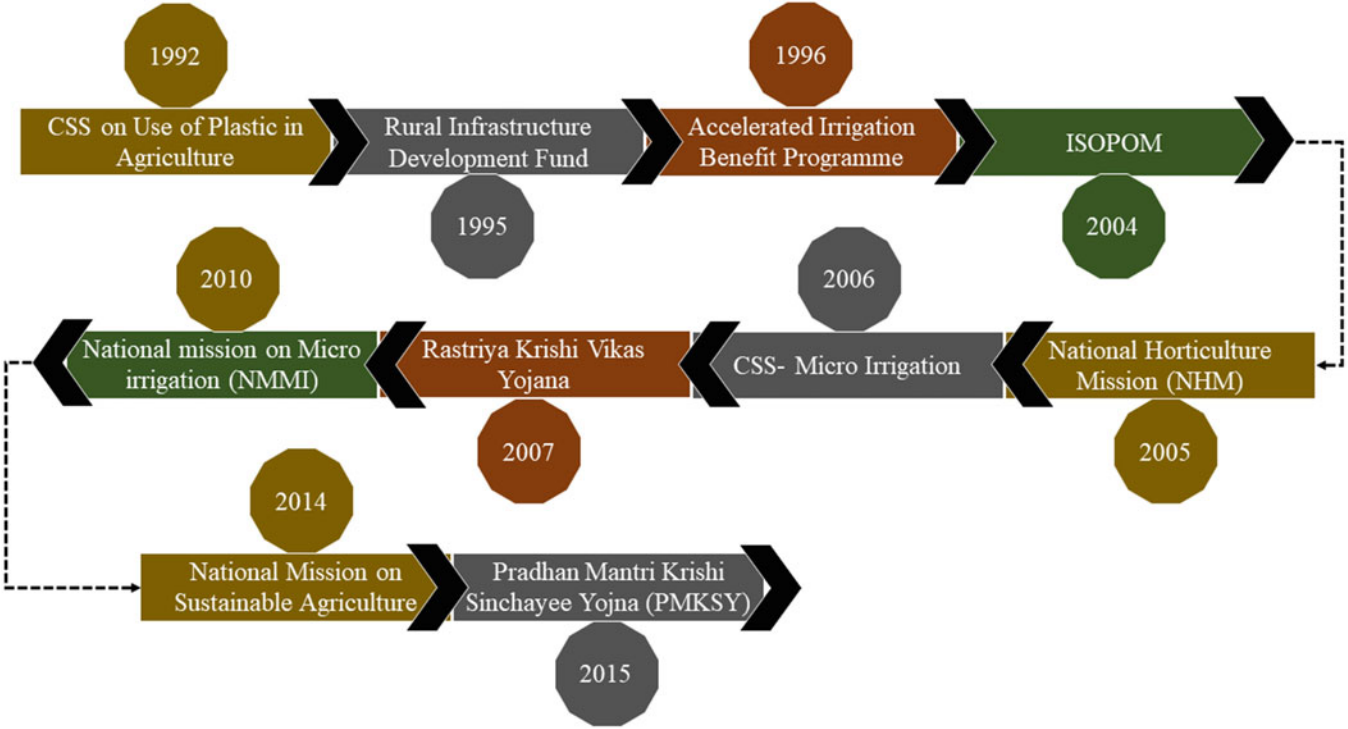


**Fig. 10.4** Schematic timeline of different schemes in India for micro-irrigation development

## 10.3 Climate Change and Water Use Efficiency

### 10.3.1 Water Use Efficiency (WUE): A Concept

Efficiencies are the ration of inputs to the outputs in any system (Hillel 1997). Hence, water use efficiency (WUE) refers to the output generated from agriculture in relation to the water input given. The conventional efficiencies, as we all know, are unitless as they are ration of two parameters with same unit (Purcell 1999), but for WUE it does have unit like total crop yield (mass) divided by total volume of water applied. In particular, the yield produced from unit quantity of water, irrespective to source, is considered in agriculture (Ali and Talukder 2008). However, the term differs with respect to point of reference like crop water use efficiency, farm water use efficiency, and irrigation project water use efficiency.

Crop productivity is interchangeably used with crop WUE at crop level and use unit of kg $\mathrm{ha}^{-1}$ $\mathrm{mm}^{-1}$ or kg/$\mathrm{m}^3$. Allen et al. (1998) gave the WUE at crop level in two ways, i.e., crop WUE (Eq. 10.1) and irrigation WUE (Eq. 10.2) while considering the water used in evapotranspiration process by crop and water applied as irrigation to the crop, respectively, as follows:

$$\text{Crop WUE} = \text{Crop Yield}\left(\text{kg ha}^{-1}\right)/\text{Crop Evapotranspiration (mm)} \tag{10.1}$$

$$\begin{aligned}&\text{Irrigation WUE}\\&= \text{Crop Yield}\left(\text{kg ha}^{-1}\right)/\text{Water Used for Yield Production}\left(\text{m}^3\ \text{ha}^{-1}\ \text{or mm}\right)\end{aligned} \tag{10.2}$$

Sometimes, apart from these efficiencies, several other efficiencies are also considered like water conveyance efficiency (WCE), water application efficiency (WAE), etc. and can be found in literatures (Purcell 1999; Evett et al. 2001).

In WUE there are two terms involved: one is input and other is output. The WUE will increase in relation to the positive and negative change in numerator and denominator, respectively, whereas it will decrease in proportion with the decrease and increase in numerator and denominator, respectively. In order to increase the WUE, one has to focus to increase the yield of crop (for given quantity of input water) or decrease the water amount input (for given quantity of output yield). In irrigation the losses occur generally in process of conveyance (seepage, leakage, or evaporation), deep percolation, and tail water runoff during this process (Allen and Pruitt 1986), and values of these losses depend on irrigation method. The effectiveness of water given as input to the crop increases when associated losses are reduced. The different irrigation techniques (water application methods) have been reported with different WUE (Table 10.1).

**Table 10.1** Water use efficiency under irrigation methods

| Water application method | Water use efficiency (%) |
|---|---|
| Flood | 65 |
| Furrow | 80 |
| Sprinkler | 85 |
| Drip | 90 |
| Overall efficiency (surface water system) | 30–65 |
| Overall efficiency (groundwater system) | 65–75 |

Source: CWC (2014)

### 10.3.2 Climate Change Impact on Water Availability, Demand, and WUE

The climate is changing, and its impacts on agriculture are mainly driven by the water and its related ecosystem (IPCC 2014; UN-Water 2018). As agriculture leads all sectors with requirement of 70% of available global freshwater (Fischer et al. 2007), the impact of changing climate on water in terms of its availability, demand, and utilization in agriculture is of utmost importance in order to understand necessary modification and adoptions in irrigation technologies. The alteration in climatic parameters influences the temporal pattern and spatial distribution of rainfall in particular and all other weather parameters in general. The changes in rainfall characteristics influence surface water distribution, runoff volume, and groundwater recharge.

Betts et al. (2011) estimated average temperature rise of 1.1 and 6.4 °C by the end of the twenty-first century under greenhouse gas emission scenarios. Hence, changes in temperature would affect the evaporation, evapotranspiration, available soil moisture, and thus availability of water to the plant/crop (Yang et al. 2011; Hipsey and Arheimer 2013). Several studies reported variation (spatial and temporal) in precipitation patterns and suggested it will be continued for decades at global scale as well as in Indian (Luo et al. 2014; Priyan 2015; Huang et al. 2018). The study on rainfall-runoff relationship under climate change indicates that runoff from instance events will also increase and that will impact process of natural groundwater recharge; hence, available water for irrigation from aquifers will be adversely impacted (Carter 2007; Amarasinghe and Sharma 2008; Shah 2009).

Impact of climate change on irrigation water demand was studied in several researches. Asokan and Dutta (2008) estimated that till 2050 there will be huge rise in water demand from different sectors including agriculture; however, after 2050 a decreasing trend would be observed due to desired regulations on population expansion. Chatterjee et al. (2012) found increased irrigation water requirement (IWR) by 14 to 15% by 2050 under climate change for Ganga River basin (West Bengal area) considering potato (*Solanum tuberosum*) as reference crop. For other crops (paddy, sugarcane, permanent garden, and semidry crops) rise in annual IWR is predicted in Bhadra command area (Rehana and Mujumdar 2013). Parekh and Prajapati (2013) were also reported increasing trend in crop water requirement for hot weather crops (millets, maize, groundnut, and small vegetables). Mohan and Ramsundram (2014) developed climate crop water requirement (CCWR) framework to study IWR and impact of climate change on it and found 5% rise in IWR for Manimuthar River basin India.

Climate influences the water regime (water availability and demand) and temperature in view of agriculture hence plays a crucial role in production (Lal 2005). There are several factors involved in studies of climate change impact on WUE and crop production, for example, conceptualization and application of climatic models, soil water content (Eitzinger et al. 2001), fertility of soil (Sirotenko et al. 1997), and other weather-related parameters (Amthor 2001) along with that from crop models. The WUE is one of the techniques to tract investment on and output from water (Zwart and Bastiaanssen 2004) and involves water-saving technology for irrigation. WUE incorporates the production (output) and evapotranspiration (utilized for production) as ratio for its numeric calculation that makes us to infer the impact of environmental fluctuation under climate change on agriculture (Walker et al. 2004), which is a step closer to manage the agronomical practices and irrigation technologies in order to mitigate and adopt future climate change impacts. Crop WUE has found to have negative relation with annual temperature and rainfall (Zhang et al. 2012, 2015). While minimizing the excessive irrigation and through improvement of deficit water conditions in field, the crop WUE can be substantially improved. The improved WUE helps the crop to sustain and adapt situation against drought in arid areas (Chen et al. 2010).

## 10.4 Advances Micro-Irrigation Technologies for Enhancing Water use Efficiency

Sustainable agricultural water management is balancing between water supply and demand in terms of quantity, quality, location, and time while minimizing environmental impact. Technical issues, rural society issues, economic issues, a legal and administrative framework, etc. impede the irrigation development plan's implementation. As a result, irrigation time and irrigation method are inextricably linked because the irrigation method impacts irrigation frequency. India has invested much in massive reservoirs and canal systems to absorb river water. Despite government efforts, the water consumption efficiency of these irrigation systems remains low due to seepage and evaporation losses. These irrigation designs have also over-irrigated and salinized canal banks, rendering millions of hectares unfit for cultivation. Due to the rapid development of food production required to feed a growing population, solutions must be discovered to reduce water usage while enhancing agricultural productivity. Micro-irrigation has emerged as the favored solution, reducing water usage while increasing agricultural productivity. Micro-irrigation techniques improve productivity and irrigation efficiency while saving water and fertilizer and minimizing groundwater and surface water pollution by generating insignificant irrigation return flow. This section describes the advances in micro-irrigation technique and the potential and challenges of micro-irrigation in enhancing water use efficiency in the dryland ecosystem.

Micro-irrigation techniques have gained acceptance globally due to their more comprehensive range of benefits. Also, new technologies enable a broader range of uses. Water filtering and clogging have historically plagued micro-irrigation. In water-stressed regions, the introduction of practical and cheaper sand and screen filtering equipment has helped combat this obstacle. Micro-irrigation integrated with efficient irrigation scheduling allows precise irrigation application specified by the crop's water requirements. Irrigation scheduling accounts weather, soil, and crop evapotranspiration rates (Jones 2004) for efficient planning, designing, and operation of irrigation system. Precision irrigation reduces runoff and energy usage, saving both water and money. Also, correctly watering crops based on their growth stage at sowing might increase agricultural yield. To help farmers schedule drip irrigation treatments more precisely, Jaria and Madramootoo (2011) showed applicability of automated moisture sensors and meteorological readings to sense irrigation event and record in a computerized system. More inventive water management strategies can be formulated to learn more about the plant, soil, and water continuums. Advancements in micro-irrigation technologies applications have been described in subsequent headings.

### 10.4.1 Deficit Irrigation (DI)

Previous water supply restrictions did not account for crop irrigation needs. Water shortage is the primary factor limiting productivity in arid and semiarid environments. It is impossible to apply the entire crop water required to sustain maximum yield potential (Konopka et al. 2009; Eissa et al. 2013). Soil moisture requirements were adjusted to suit the crop better. However, increasing municipal and industrial water needs in dry and semiarid areas rapidly reduces agricultural water allocations. As a result, water is often scarce and insufficient to maximize yields. To enhance water use efficiency, use irrigation methods that do not consider overall crop water requirements. By applying less water than the crop's total requirement, deficit irrigation reduces irrigation water consumption and conserves available water resources. Stressing crops enhances water usage efficiency, but not yields (Fereres and Soriano 2007). Under such conditions in the dryland farming system, micro-irrigation techniques enable sustainable crop production by employing deficit irrigation techniques.

### 10.4.2 Partial Root-Zone Drying (PRD)

Partially drying the root zone can also aid in efficient irrigation water use when using micro-irrigation technologies. The PRD system is a modified deficit irrigation system. The aim of a PRD is to irrigate and dry half of a crop's root system regularly. Crop type, development stage, and water requirements are all factors that influence alternating crop frequency. A thorough understanding of the mechanisms that affect transpiration and experience with administration and monitoring is required to use this strategy effectively (McCarthy et al. 2002). According to the researchers, PRD can cut water consumption while enhancing canopy vigor and, eventually, yields in water-stressed areas. Compared to properly watered crop plants, the PRD irrigation technology decreased water use by 35% while causing a biomass decline of approximately 6–11% in the maize crop (Kang and Zhang 2004). According to the findings, another research study on hot pepper crops that used drip irrigation technology found that PRD reduced water usage in irrigation by 40% while providing the exact yield as thoroughly watered crop plants (Kang et al. 2001).

### 10.4.3 Alternate Partial Root-Zone Irrigation (APRI)

Alternative partial root-zone drip irrigation (ADI), also known as alternate partial root-zone drip irrigation (APRI), is the water-saving approach that supplies alternate wetting and drying cycling to the root-zones, which can minimize irrigation water usage (Kang et al. 1997; Kang and Zhang 2004). Research on a variety of crops, including maize, potato, peach, and cotton, has revealed that APRI or ADI is effective in boosting water use efficiency (WUE) without causing a significant reduction in yield (Song et al. 2008; Du et al. 2008; Li et al. 2007).

### 10.4.4 Wastewater Application Using MIS

Micro-watering technology provides customized irrigation in water-stressed areas. Both treated and untreated wastewater can be sprayed selectively on crops. Micro-irrigation is better for wastewater reuse than conventional watering since it does not produce aerosols or interact with plants. There are also fewer odors, ponding, and drainage issues. Aside from that, research shows that applying nitrogen directly to plant roots speeds up absorption and reduces groundwater pollution. Frequent checks are required to maintain consistency and full functionality (Casey et al. 1999).

### 10.4.5 Reverse Osmosis Subsurface Drip Irrigation

Water scarcity can be alleviated by incorporating reverse osmosis equipment into underground drip irrigation systems. A process known as reverse osmosis allows for applying brackish water, widely found in groundwater formations, as an irrigation supply. Because water extraction is proportional to the crop’s need, reverse osmosis subsurface drip irrigation systems use water efficiently (Leslie 2010).

### 10.4.6 Internet of Things (IoT) in Micro-Irrigation

The Internet of Underground Things (IoUT) is a novel perspective on the Internet of Things (IoT) (Vuran et al. 2018). There will be both underground and aboveground Internet of Things devices that will communicate with one another using underground-underground, underground-aboveground, and aboveground-aboveground communication protocols. Moreover, finding new materials that are both weather-resistant and do not significantly increase the cost of the devices may be difficult. However, the use of recyclables in some aspects of IoT devices is expected in the near future (Tseng et al. 2019).

### 10.4.7 Soil Moisture Sensor in Micro-Irrigation

Techniques for measuring soil moisture that is considered traditional encompass thermogravimetric methods, calcium carbide neutron scattering, such as (time domain reflectometry (TDR); frequency domain reflectometry (FDR); capacitance technique; and optical methods), among other instruments (Blonquist Jr et al. 2006). Thanks to sensor data collection, actual water content may be determined in real time, on-site, and reasonably low cost. Sensors may one day provide the ability to irrigate in line with the distinct characteristics of a particular crop in a specific land (Thompson et al. 2007).

## 10.5 Potential and Challenges of Micro-Irrigation in Dryland Agriculture

Micro-irrigation techniques hold great potential in the dryland agriculture system to enhance water use efficiency. These techniques have been used in association of other water-saving techniques such as mulching (organic and inorganic) and protected cultivated structures among others. Many hurdles must be overcome before micro-irrigation can be extensively adopted, especially in poorer countries with small farms. Close-growing crops like rice or wheat are often unsuitable for this watering system (Brouwer et al. 1988). As a result, farmers that plant these close-growing crops have been unable to profit from micro-irrigation. On the other hand, micro-irrigation is becoming more widely applicable as technology advances. Drip irrigation has shown a reduction in water usage by 50–60%. Drip irrigation helps keep soil moisture levels near the crop’s needs during the growing season. The absence of flooding stimulates weed growth and enables herbicide application through drip irrigation for rice production (Soman 2012). In places that rely on cereal crops for sustenance, a better understanding of their water requirements is essential and more appropriate equipment and technology. The benefits of subsurface drip irrigation over surface drip irrigation are currently being researched. Because field workers and rats are less likely to harm or interfere with underground systems, they tend to last longer. Recent research shows that underground drip lines produce plant yields comparable to or higher than surface drip lines. Subsurface irrigation methods also use less water and fertilizer than surface irrigation systems. However, specific advanced subsurface drip systems require air entry apertures and flushing manifolds. A dry soil surface is helpful in some situations (e.g., to reduce weed growth) but harmful in others (e.g., to improve soil moisture) (i.e., for germination of shallow-planted seeds). Subsurface irrigation can also be employed for wastewater purposes. Also, deeper phosphorus distribution in the soil profile promotes plant phosphorus uptake, decreasing smell concerns (Camp et al. 2000). More research is needed to determine the best location for soil moisture sensors as we go toward automated irrigation scheduling. Solvent sensors currently provide limited information on soil moisture status and depth inside a site at a given place. Thus, sensor placement is crucial for obtaining a representative measurement that can be used to identify the best irrigation strategy. Positioning the sensor near the wetted region of the crop root zone is crucial for controlling irrigation. Thermal vision from low-flying unmanned aerial vehicles like drones, planes, or satellites can precisely measure soil water content or plant water status. These improvements can improve crop production and water conservation. This method can overcome obstacles, including soil heterogeneity and field unpredictability, ensuring local water needs are met. Crop simulation models and remote sensing have been created (Barnes et al. 2000). More research is needed to increase accuracy and cost-effectiveness. Nano- and biotechnology in micro-irrigation can benefit water quality, filtering, and emitter clogging, among other things. On-site nanomaterial-based biosensors can detect, measure, and monitor pollutant presence in real time. Nanofiltration membrane technology allows for particle detection, capture, and partial water desalination. This reduces membrane and filter fouling. Nanotechnology soil moisture sensors have great accuracy, fast response times, and corrosion resistance.

The challenge with these advancements is their practical application. Affordability, availability, and informed management influence the adoption of these promising technologies (OECD 2011). Despite technological advances and simplification, micro-irrigation devices remain prohibitively expensive. Significant technical skill is required to design, maintain, and operate systems efficiently and effectively. Farmers will be more interested in this technology because of the initial cost and labor reductions. Small farmers in developing countries have been slow to adopt micro-irrigation due to the high initial costs. Other factors contributing to its unacceptability include lack of funds, knowledge, and crop specificity associated with current micro-irrigation systems (Varma et al. 2006). Studies show that new technology's potential for conserving water and energy does not sway farmers. With no water meters and substantially subsidized energy, farmers have no financial incentive to save resources.

Furthermore, farmers who have relied on surface irrigation for decades and are used to receiving water via canals see no immediate benefit in switching to other irrigation methods such as drip irrigation. Farmers are always looking for innovative ways to increase their income and production (Soman 2012). Micro-irrigation technology will require increased institutional and financial support, product subsidies, and cash availability in developing countries (Varma et al. 2006).

## 10.6 Conclusions

The dryland regions, i.e., 41% of the global terrestrial, are dominated for grazing and rainfed cropping because of water scarcity, and the crop water productivity generally remains low due to on-farm water losses through seepage and evaporation. Drylands show a wide diversity and, therefore, require appropriate sustainable best mitigation practices and strategies. In the limited water resource environment, advanced micro-irrigation techniques play an important role, and these methods are helpful in improving water use efficiency (WUE). Globally, 40% of the total food and fiber is produced through irrigation only; therefore precise assessment and management of micro-irrigation techniques are required.

This chapter focuses on the advancement in the micro-irrigation techniques at globe and regional scale. The impact of changing climate on water in terms of its availability, demand, and utilization in agriculture is of utmost importance in order to understand necessary modification and adoptions in irrigation technologies. Major water saving from the irrigation system is the future need and that could be achieved by precise management and innovative design for water delivery and field irrigation. Previous literature showed that deficit irrigation has potential for sustainable reduction in agricultural water use. Remotely sensed data on plant and soil using integrated sensors/satellite-based real-time on-the-go irrigation scheduling can be very helpful in reduction of agricultural water losses. Artificial intelligence (AI)-based automated micro-irrigation may be helpful in water saving without yield penalty.

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# Enhancing Agricultural Water Productivity Using Deficit Irrigation Practices in Water-Scarce Regions

# 11

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## Abstract

As the world grapples with climate change concerns, particularly changes in temperature and precipitation, modifying these climate variables as a result of global warming leads to a water scarcity crisis in the country. Water scarcity is defined as annual water availability per capita is less than 1000 cubic metres, according to a World Bank assessment. Following the Falkenmark Index, water shortage exists in more than half of the country's 20 river basins, with availability of less than 1000 cubic metres per capita per annum (Singh and Kaur, India's water crisis: challenges, solutions and barriers, working paper, Rajiv Gandhi Institute for Contemporary Studies, 2019). Along with this India has endowed only 4% of the world's *freshwater* resources despite of 17% of world population clearly highlights the need for its sagacious use. The country's water availability has worsened as a result of the disproportionate availability of freshwater and the delayed monsoon as a consequence of climate change. The situation extensively affects the country's agricultural productivity which is the mainstay of Indian economy and principal livelihood for over 58 percent of the rural households. However, an ever-increasing population puts a strain on food supplies. As a result, scientific water management in agricultural practice is widely recognized

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as critical to long-term agrarian reform in water-stressed situations, which necessitates a paradigm shift away from maximizing productivity per unit of land area and towards maximizing productivity per unit of water. Keeping these facts, potent irrigation water management in a future of water shortage must be required, with the goal of conserving water and optimizing its output. In addition, a new management paradigm based on maximizing net benefit rather than yield must be implemented. This can be accomplished by lowering irrigation water demand and diverting the saved water to irrigate greater area while maintaining a relatively high water yield. To deal with this, the most important intervention is deficit irrigation, which involves purposely under-irrigating crops by applying water below the evapotranspiration requirements (English and Nuss, J Am Soc Civil Eng 108:91–106, 1982). As a result, this chapter has discussed a methodical and plausible strategy for increasing water productivity through deficit irrigation.

**Keywords**

Arid agriculture · Deficit irrigation · Water use efficiency

## 11.1 Introduction

*Dryland farming* is often defined as crop production in areas subjected to annual rainfall of less than 500 mm and specially practised in arid and semiarid regions in which annual precipitation is about 20–35% of potential *evapotranspiration*. Drylands account for 44% of the world's cultivated area and endowed with one-third of its population. It possesses only 8% of the global renewable water supply, whereas in India dryland agriculture occupies 68% of India's cultivated area and supports 40% of the human and 60% of the livestock population. It contributes 44% of food requirements, which highlights it plays a critical role in India's food security. The substantial development in drylands has been impeded due to immense pressure from the burgeoning populations, land degradation, and climate change impacts. Along with this nowadays water scarcity is the most prominent challenge that drylands face which implies the need of begin to see the lights in efficacious management of water resources. As the competition for water resource swells due to certain anthropogenic concerns and the insufficient attention paid for its management, the access of agriculture to this crucial source is no longer guaranteed for dryland condition. The chronic water scarcity scenario, worsened by the above explained reasons, leads to an imbalance between supply and demand for water (Seckler et al. 1998; Kushwaha et al. 2016). Therefore, in a stage of water scarcity, water management needs to be rationalized in a scientific manner to ensure efficient water saving and maximized productivity.

Apart from this in water-scarce areas releasing of water to other sectors with maintaining the productivity to meet the demands raised is a complicated picture. However, Food and Agricultural Organization (2012) estimated that to meet the demand of future 80% of the additional production is required which can be fulfilled by intensification and enhancement of yield. Hence there has been a paradigmatic shift of increasing productivity per unit land towards increasing productivity per unit water consumed which heightened by limited possibilities for extension of more irrigated areas (Shanan 1992a, b; Kushwaha and Kanojia 2018). The strategy of supply irrigation with abundant water up to the maximum ET requirements to enhance the yield becomes challenging in water-scarce region. Therefore, a plausible and robust strategy is mostly needed to limit the available water supply with insignificant reduction in yield. In this situation rather than covering the whole land, small area should be concentrated, or irrigate the total area below full ET requirements.

Taking these above said concerns in account deficit irrigation is an assuring solution to lessen the supply-demand gap of water in dryland regions. Below ET-based application of water is termed as deficit irrigation (English et al. 1996). This strategy differs from the traditional one by actively managing the crop water stress during the growing season (Klocke et al. 2007). Though producers can obtain maximum profit by propitiating entire crop water requirements, practicing deficit irrigation as a consequence of limited water supply can increase the irrigated area by saving considerable amount of water. Application of water on the right time can galvanize the enhancement of water use efficiency for most of the crops. During growing season a rationalized irrigation management should be allowed to double the area covered by crops with minimum decrease in yield loss and substantial fetching of economic return considering the economic standpoint, whereas according to Zhang et al. (2018), the optimization of irrigation water application revolves around the estimation of crop water use, determination of irrigation scheduling, and proper management of agronomical measures.

Nevertheless, on the basis of these background information, the focus of this chapter is on providing a clear-cut understanding about deficit irrigation, intervention of new techniques to enhance water use efficiency with limited water supply, management of soil and water in deficit irrigation, and its economic analysis which will definitely provide new avenue for the betterment of DI practice in water-scarce situation.

## 11.2 Definition and Feature of DI

Deficit irrigation (DI) is a reasonable and manageable depletion of water to enhance water use efficiency (WUE) for higher yields per unit of consumed water. As stated by English, DI can be defined as "methodical and systematic under-irrigation of crops" (English 1990; English et al. 1996) integrated with development of methodical framework to maximize the profit with restriction of water availability. Behind this approach a certain level of water stress is allowed during a particular period or for the whole growing season. Apart from this Chai et al. (2016) defined water deficit for different level of field capacity:

- Severe water deficit—soil water $<$ 50% of the field capacity.
- Moderate water deficit—soil water $=$ 50 to 60% of the field capacity.

- Mild water deficit—soil water = 60 to 70% of the field capacity.
- No deficit or full irrigation—soil water > 70% of the field capacity.
- Over-irrigation—amount of water application > optimum crop water requirement.

This irrigation strategy is considered with an expectation that benefits gained from the conserved water should be greater than insignificant reduction in yield (Fan et al. 2014; Pereira et al. 2012). Despite of reduction in yield, this strategy has opportunities of maintaining considerable quality of crop compared to full irrigation condition. However, the response of crop yield to water stress at critical growth stages or throughout the growing season and maximum allowable with minimum reduction in crop yield is necessary to be known before adopting deficit (Kirda and Kanber 1999). Along with this pertinent knowledge of crop ET, identification of critical crop growth periods, and the economic impacts of yield, reduction strategies are needed for the adaptation of DI. However, the soil salinity consequence of limited water used by DI raised due to lack of leaching and its impacts on sustainable water management have been considered as greater risk (Schoups et al. 2005). In spite of certain limitation, DI can contribute to (i) reducing overall water demand, (ii) reducing declination of productivity of land, (iii) decreasing operation and maintenance cost, (iv) fixed amount of water increase in areas under irrigation, and (v) upliftment of economic return and food security (Geerts and Raes 2009).

There are certain factors that need to be considered before adopting deficit irrigation. Sensitivity of crop growth to water deficit is an essential factor in this strategy. Hence it is preferred to select crop having high water resistance. In deficit irrigation, short-growing and drought-tolerant crop varieties are more suitable (Stewart and Musick 1982). Generally, high-yielding varieties (HYVs) are more water-sensitive than low-yielding varieties. For example, new maize varieties show poor result in deficit irrigation compared to the traditional verities (Food and Agriculture 1979). Apart from this to achieve blooming and robust deficit irrigation strategy, soil parameter also plays an important role. To ensure this concept, soil water retention capacity should be considered. In sandy soil crops may be exposed to water stress very quickly compared to those in fine-textured soil. Low soil matric pressure can be easily maintained in fine-textured soil without affecting the soil water content. Therefore, successful deficit irrigation is more relevant to fine-textured soil.

## 11.3 Types of Deficit Irrigation

PRD and RDI strategies are the most important types of DI which involve enhancement of crop water use efficiency by manipulating in irrigation water application and deficit of moisture within the root zone. On the basis of maximum crop ET-based water supply level, each DI situation can be defined. In this chapter two major types of deficit irrigation have been discussed.

### 11.3.1 Regulated Deficit Irrigation

According to English et al. (1990), regulated deficit irrigation modified as controlled deficit irrigation is a conscious restriction of irrigation water which may be a justifiable management during certain crop-growing phases to manipulate crop water use (Chalmers et al. 1981). At different crop development stages, RDI (RDIC) is a standardized approach where critical growth stages (most sensitive growth stages) are supplied by full irrigation and noncritical growth stages are restricted by limited water application. This practice imposes water stress during insignificant yield reducing crop-growing phases with considerable maintenance plant water status below the permissible limits of deficit to control vegetative and reproductive growth (Chalmers et al. 1981; Li et al. 1989; Girona et al. 1993; Kriedemann and Goodwin 2003). RDI has been often demonstrated to be an optimized tool for water use efficiency (WUE) for different crops such as citrus, grapes, pears, (Romero et al. 2013; Cui et al. 2008; Panigrahi et al. 2014; Chalmers et al. 1981; Matthews et al. 1987; Mitchell et al. 1989; Girona et al. 2006). sugar beet (Miller and Hang 1980; Fabeiro Cortes et al. 2003), cotton (Snyder 1992), and tomatoes (Hsiao 1993). Precision irrigation strategies are the paramount for a successful application of RDI by taking into account the timing control and soil water level monitoring. According to Kriedemann and Goodwin (2003) in regulated deficit irrigation, size and quality of fruit and vegetative growth can be controlled fruit size and quality, vegetative growth can be achieved.

### 11.3.2 Partial Root Zone Drying

Partial root zone drying (PRD) is where half of the root system is irrigated, while the remaining half is exposed to drying soil. The principle behind this approach is considering a frequency at which previously well-watered side of the root zone should be dried down while the previously dried side is fully irrigated and the alternate partial wetting and drying of the root zone is done. In this strategy alternate plant sides are imposed by a percentage of crop evapotranspiration which is ensured by allowing partial wetting of root system. However partial root zone drying is based on two assumptions: (1) dried partial root zone tends to send root-shoot signal (induced by Abssisic ABA) to limit the stomatal aperture for limited transpiration (Dry and Loveys 1999), and (2) with limited availability of water, a partial closing of stomatal aperture may be effective in reducing loss of water substantially with insignificant impact on photosynthesis (Dry and Loveys 2000). The concept of PRD depicted in Fig. 11.1 is hypothesized for water use efficiency enhancement and reduced vegetative growth, stomatal conductance by root to shoot signalling induced by abscisic acid (ABA) during alternative drying and wetting of root zone (Wang et al. 2012). In this strategy the crop growth and development are not affected as the decrease in leaf water potential has no effect on decrease in irrigation to the part of the root zone, and instead the protective process of plant may be stimulated by PRD. PRD has been represented as a potential technique in saving water and enhancing water use efficiency (Wang et al. 2012; Kang et al. 2001; Guang-Cheng

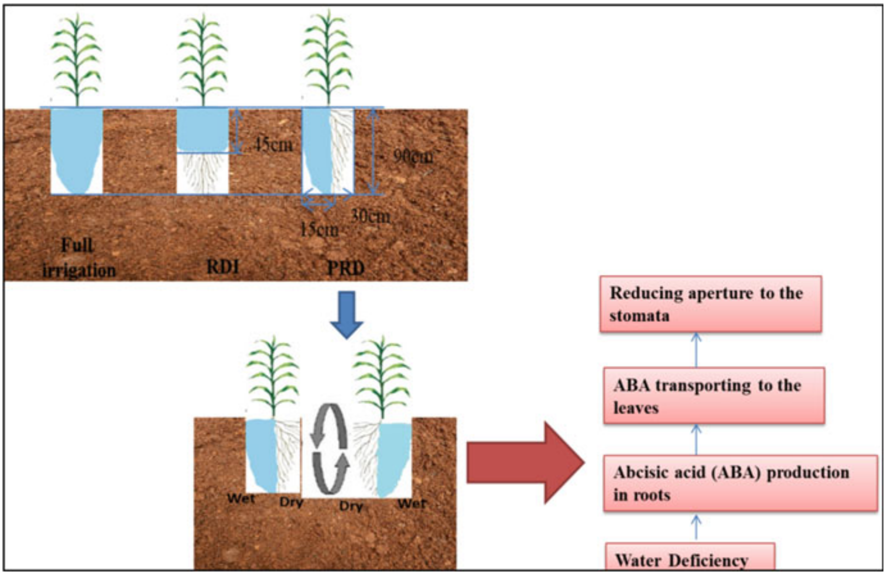

**Fig. 11.1** Schematic diagram of partial root zone drying method

et al. 2008; Wakrim et al. 2005; Savic et al. 2008; Stikic et al. 2003. The nature of the confined soil moisture and crop water status conditions (Ruiz-Sanchez et al. 2010) makes PRD to be differed from RDI.

## 11.4 Water Productivity and Deficit Irrigation

At present, the consequence of global expansion of irrigated areas and the restricted availability of irrigation water compel to adopt appropriate water management to achieve efficient use of water. Increase net economic return per unit consumed water should be concentrated instead of per unit land when limited water supply is concerned. Recently, water productivity concept has been emphasized which is defined as the yield per unit of water used in evapotranspiration (Kijne et al. 2003a, b). This leads to reduce ultimately maximum investment returns and production costs and simultaneously supports the sustainability under frequently occurring situations of deficit irrigation. Oweis et al. (1998) and Zhang et al. (1998) stated that the concept of water productivity revolves around optimal irrigation schedules when multifactorial field trials derive different strategies for deficit irrigation. When specific crop development period is exposed to water deficit, there is a variation in yield response based on sensitivity of crop at different growth stage. Therefore, in order to minimize the yield loss, controlled time of irrigation is appropriate tool for scheduling irrigation. According to Kirda (2002), careful evaluation is needed in irrigation scheduling to ensure enhanced efficiency in limited water supply condition.

Moutonnet (2002) further stated that when there is a maximum reach of evapotranspiration, then the yield approaches to the maximum value. Generally, a significant reduction in soil water storage affects the crop water availability which ultimately affects the actual yield and evapotranspiration. A standard formulation represents a relative yield decrease to relative evapotranspiration deficit including the yield response factor (Ky), (Food and Agriculture Organization 2002) earlier used by Stewart et al. (1977) which is given below:

$$\frac{Y}{Y\mathrm{m}} = 1 - k\mathrm{y}\left[1 - \left(\frac{\mathrm{ETa}}{\mathrm{ETm}}\right)\right] \tag{11.1}$$

Here $Y$ is actual yield (kg/ha).
$Y$m is maximum yield (kg/ha).
ETa is actual evapotranspiration (mm).
ETm is maximum evapotranspiration (mm).
$K$y is yield response factor.

A crop yield response factor is known as water production function ($k_{\mathrm{y}}$) which depends upon several factors such as species, variety, irrigation method, management, and growth stage when deficit evapotranspiration is imposed. It indicates the unit change in yield as there is a unit change in evapotranspiration. When its value exceeds 1, it indicates that the relative decrease in evapotranspiration is proportionality lower than expected relative yield decrease for a given evapotranspiration deficit (Kirda et al. 1999a, b), and it is vice versa for when its value less than unity. Nevertheless it has been experimented that relative to under full irrigation, WP increases under DI for many crop (Zwart and Bastiaansen 2004; Fan et al. 2005; Ozbahce and Tari 2010; Kumar et al. 2018) and the regression analysis for WP increment and yield reduction versus saved water represented higher values, which indicates that DI could be an option for enhancement of WP and increasing overall yield by expanding irrigated area and applying the saved water in water-scarce region.

In Table 11.1 yield response factors for different crops where there is a less yield reduction compared to relative evapotranspiration deficit have been presented (Kirda et al. 1999a, b).

Elias and Soriano (2007) has stated that limited irrigation amounts increase crop ET; the relationship between ET and yield is found to be linear up to a certain point where it turns curvilinear because some fraction of water applied is not contributed in crop evapotranspiration and is neglected. After hitting the peak point where yield approaches its maximum value, then further addition of water does not have any effect on yield increase. However, the uniformity in irrigation is needed to approach the maximum yield for given amount of water. According to Elias and Soriano (2007), it is also important to highlight the need of irrigation systems of high application uniformity under DI so that the over-irrigated area should be restricted

**Table 11.1** Crop response factors for different crops

| Crop | Specific growth stage | $k_y$ | Reference |
|---|---|---|---|
| Cotton | Flowering and yield formation | 0.99 | Bastug (1987) |
| | Whole season | 0.86 | Yavuz (1993) |
| | Bud formation; flowering | 0.75<br>0.48 | Prieto and Angueira (1999) |
| | Boll formation; flowering, vegetation | 0.46; 0.67; 0.88 | Anac et al. (1999) |
| | Flowering | 0.74 | Ahmad (1999) |
| Maize | Whole season | 0.74 | Craciun and Craciun (1999) |
| Soybean | Vegetative | 0.58 | Kirda et al. (1999a, b) |
| Sugar cane | Tillering | 0.40 | Pene and Edi (1999) |
| Wheat | Flowering and grain filling | 0.39 | Waheed et al. (1999) |

by limited supply and under-irrigated area should be irrigated to deficit level to enhance the water productivity.

According to Kirda et al. (1999a, b), water use efficiency at deficit ET is 1.09 times higher than at full irrigation. This indicates that there is a compensating effect between the increased irrigated area by saved water and the yield loss. Throughout the season if the planned ET is imposed, then the total irrigation water saved can be calculated on the basis of crop water requirement. However, it is crucial to know the water requirement of crop if the stress is presumed during a specific growth stage, to quantify the water saved. This concept is very much important to select crops which have lower crop yield response factor ($k_y < 1.0$) to achieve significant irrigation water savings with an considerable increase in water productivity. Where as it has been studied that at high yield level water productivity decreases i.e., enhancing water production tends to lower yields. Example in Northern Syria, Oweis et al. (1998) reported that 10–15% yield will be reduced when 50% of full supplemental irrigation requirement is satisfied.

However, there is a lack of precession in knowing the yield function and the water use cost. Due to this fact, there is an uncertainty associated with this type of irrigation system. There is a difficulty in estimation of water losses which is contributed by different components when there is a variability related to weather, soil, and topography; the yield function tends to be uncertain. It is also difficult to predict, for a given amount of root zone stored soil water, what yield would be produced which ultimately contributes to economic risk (English et al. 1990).

## 11.5 Deficit Irrigation Scheduling

Deficit irrigation can be successfully applied when there is a better understanding about when and how to irrigate. According to Goodwin and Boland (1998), scheduling has been relied on pan evaporation (Epan), soil moisture measurement, and plant response before taking management decision. Pereira (2001) reported that through validation and calibration of simulation models, the irrigation scheduling strategies for deficit irrigation have been generated. This modelling approach includes the yield-water function by which the yield impact of water deficit can be evaluated. El Amami et al. (2001) concluded from this study that when there is ten times reduction in available water, it decreases the yield per unit surface cropped land, but the yield per cubic metre of water applied is increased. Therefore, for each irrigation strategy, land should be allocated to crop based on balance between economic return and cropped area; for a low deficit irrigation, the water productivity increases and decreases afterwards when there is a severe deficit. Therefore, according to Kirda et al. (1999a, b), cropping only a fraction of land rather than the full land is the best option for deficit irrigation. It implies scheduling of deficit irrigation requires not only knowledge of crop but also the yield response to water. However, controlling time of irrigation and crop water stress identification are the best approach to for scheduling the deficit irrigation. According to Goodwin and Boland (1998), in the case of drip irrigation, for scheduling RDI the time of run can be calculated by a standard formula based on $E_{\text{pan}}$ which is

$$\text{Run time} = ((\text{Epan} - \text{Rain}) * \%\text{Replacement} * \text{Row spacing} * \text{Plant spacing}) / _{\text{Emitter rate per plant}} \tag{11.2}$$

Where, run time is in hour, rainfall is in mm, plant spacing and row spacing are in m, and emitter rate is in litres/h.

Apart from estimation of run time, determination of irrigation interval is also important for scheduling deficit irrigation for system other than trickle. According to Mitchell and Goodwin (1996), the formula for calculation of irrigation interval based on average daily pan evaporation is the following:

$$\text{Interval (days)} = \frac{\text{Volume of water in root zone(litres)}}{\text{Average daily ater use } \left(\frac{\text{litres}}{\text{day}}\right)} \tag{11.3}$$

Precise determination of crop water stress based on different strategy enhances the proportion of water saving. According to Carmen et al. (2018), in water stress condition, water stress threshold can be determined by different water stress detection technologies such as physiological sensor, dendrometry, thermography, and soil water content measurement depicted in (Fig. 11.2) which is related to yield and fruit quality, nutritional status, and water saving. By water production function, the amount of water saved can be estimated and water use efficiency which decrease in case of over irrigation. Based on these two factors, plausible strategy can be determined for deficit irrigation.

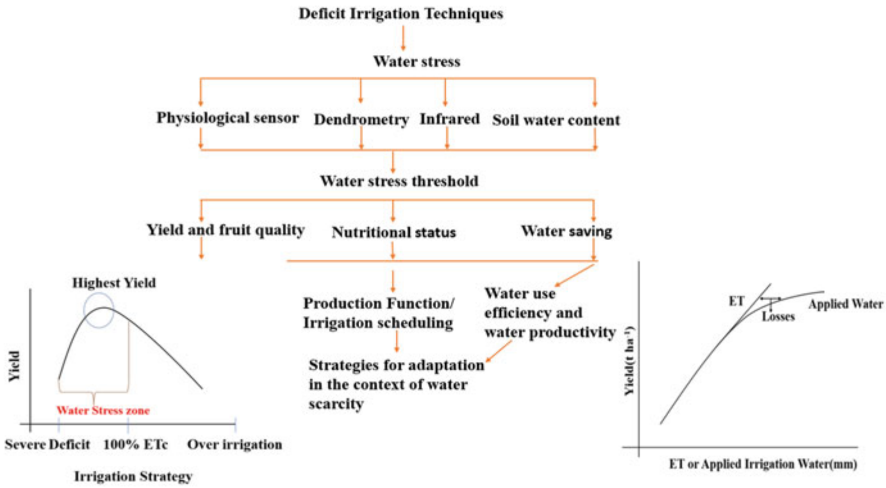

**Fig. 11.2** Schematic diagram on irrigation strategy based on water scarcity scenarios

## 11.6 Techniques for Enhancing Water Use Efficiency

Dryland farming, which is common in semiarid and arid regions, is basically crop cultivation process where water supply is a key limitation. According to ACIAR (2002), dry land farming can be defined as agricultural areas in which the average water supply of the crop limits potential production to less than 40% of full production (without water). Various factors like soil erosion by wind and water, depletion of organic matter content (OMC), salinity and chemical deterioration, etc. contributed to soil degradation in dry environments. Apart from it, the water availability for crop use, as well as its spatiotemporal distribution, is a major challenge in dryland agriculture. Desertification also occurs in the worst circumstances. Despite of it, degradation mechanisms are often considerably more prevalent than soil conservation techniques in dryland environments, allowing the soil resource base to swiftly erode. As soil quality deteriorates, infiltration rates and water-holding capacity decline, making an already scarce water resource increasingly less efficient, resulting in a negative twist in soil-water quality and crop productivity in dryland agriculture. Processes of soil degradation and conservation practices have a complex relationship with soil quality (Fig. 11.3).

To enhance agricultural production and improve water use efficiency, suitable tillage and residue management strategies, well-adapted varieties of crops, and fertility management are required. Water harvesting, which concentrates/collects runoff water from non-cropped regions and applies it to neighbouring agriculture, is another method for improving productivity in specific circumstances. Generally, the options to improve water use efficiency in dryland regions are categorized into two major sections: agronomic and engineering practices. Detailed description of

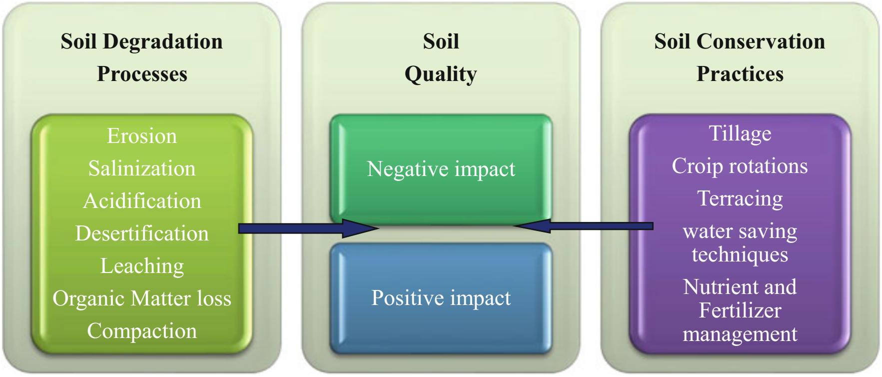

**Fig. 11.3** Relationship of process of soil degradation and conservation practices with their quality

agricultural practices including both agronomic and engineering has been given below.

### 11.6.1 Agronomical Measures

Agronomic measures basically include different types of bench terraces, contour bunding, contour strips, strip cropping, cover crops, crop rotation, off-season and deep tillage, summer fallow, mulching, sowing in furrows, etc.

### 11.6.2 Mulching

In dryland agriculture, the primary limiting component is soil moisture. It evaporates from soil by evaporation and is lost by transpiration from canopy surfaces. Evaporation loses between 60% and 75% of the rainfall, and mulches check these losses. Mulch is any material that is placed to the surface of the soil to reduce evaporation. Apart from it, it is a water-saving practice for soil moisture conservation, controlling temperature, preventing erosion, and lowering evaporation from soil in dryland regions also (Vishwakarma et al. 2022; Kader et al. 2017; Qin et al. 2016; Yang et al. 2015). Surface mulching is an overarching water conservation tactic for rainfed systems (Chakraborty et al. 2008; Zribi et al. 2015). Plastic mulching conserves soil water better than straw mulch of wheat (Li et al. 2013). Different types of mulching like stubble mulch, straw mulch, dust mulch, plastic mulch, etc. have been used to check soil evaporation and conserve soil moisture (Fig. 11.4).

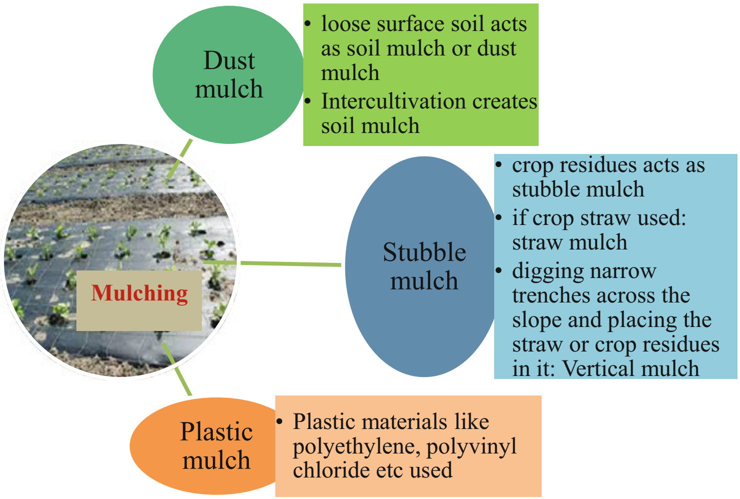

**Fig. 11.4** Types of mulching

## 11.6.3 Tillage

Tillage is often beneficial to crop productivity in dryland farming. It has several advantages, including seedbed preparation, weed control, and incorporation of excess crop residues on soil surface, fertilizers and pesticides, etc., but it can also be harmful to maintaining soil sustainability for longer durations. Tillage has a minimal impact on long-term dynamics and survival of weed seed in soil when crops rotate with diverse life cycles, i.e. crop rotations and diversifications (Anderson et al. 2006). Off-season tillage increases moisture conservation and minimizes weed development especially in alfisols, whereas in soils with hard pan, deep tillage aids in boosting water intake (Sivanappan 1995). Due to its positive consequence on soil moisture storage, conservation tillage systems like reduced tillage or no tillage have been identified as one of the most promising strategies for increasing SOC stocks in dryland areas (Aguilera et al. 2013). When adopting no tillage, significant C sequestration rates have been documented in various dryland systems (Palm et al. 2013; Farina et al. 2011; Govaerts et al. 2009; Vågen et al. 2005). Reduced tillage has a positive impact on many characteristics of the soil, but unsustainable and unneeded tillage operations have the reverse effect, causing soil damage. As a result, there is a lot of attention and focus right now on the transition from high tillage to minimal/no tillage.

## 11.6.4 Intercropping/Mixed Cropping and Crop Rotation

Agronomic practices that boost crop yield, such as intercropping and crop rotation, must be popularized in dryland regions. Crop rotation provides a number of advantages like lowering the prevalence of insect pests, weeds, and crop diseases, as well as improving the physical like better water-holding capacity and aggregate stability, chemical, and biological qualities like improvement in organic matters of the soil, etc. Crop rotation combined with a no-till system can also help with soil aggregation and water saving in intensified agriculture cropping systems, particularly in dry and semiarid climate regions (Lal 2015). Similarly, in intercropping/mixed cropping, crop water requirements for different crops can be influenced by the variation in root structures and their length in the soil profile, especially in rainfed or dryland agriculture (Nielsen et al. 2011). These systems also help in minimization of crop failure risk and enhancing water productivity of cropping systems. Intercropping has also huge potential for improvement of crop yield and water productivity (Borghi et al. 2013; Qin et al. 2013), as well as the crop yield in next year in rotational mode (Sharma et al. 2017). A combination of intercropping and deficit irrigation (Chai et al. 2014) or crop straw mulching (Yin et al. 2017) can significantly improve WUE in semiarid/arid areas (Yang et al. 2011; Fan et al. 2013). Both (intercropping and mixed) cropping systems in a broad range of situations are expected to enhance resource usage efficiency (Willey 1979; Francis 1989).

### 11.6.5 Nutrient Management

Fertilizers not only promote crop development, but it also encourages root growth, which allows water to be absorbed from deeper soil layers, which is very important during droughts. Apart from it, quick expansion of the plant canopy as a result of fertilizer application provides more shade on soil, which reduces the amount of evaporated water. Various scholars have demonstrated the positive influence of nutrient management on water use efficiency (IAEA 2005; Rao and Ryan 2004; Van Duivenbooden et al. 1999; Monteith and Webb 1981). INM (integrated nutrient management) needs to be promoted with special prominence on biofertilizers used to maintain the soil fertility in dryland areas. Biofertilizers like blue green algae, *Rhizobium*, *Azospirillum*, *Azotobacter*, vesicular arbuscular mycorrhiza, and phosphate-solubilizing organisms could be used as part of dryland agriculture's INM. Fertilizer efficiency can be increased by using biological nitrification inhibitors as well as slow and controlled release fertilizers and also led to reduction of nitrogen losses in dryland soils (Nawaz and Farooq 2016).Correct fertilizer application in the soil at sowing time can boost the production and quality of dryland crops by reducing leaching and the aerial environment (Janzen et al. 1999).Trials of balanced nutrient management have proved that agronomic efficiency of used nitrogen can be enhanced by adding P and K nutrients, 6.7 kilograms of sorghum grain per kilogram of nitrogen, 10.3 kilograms of pearl millet per kilogram of nitrogen, and 19.5 kilograms of maize grain per kilogram of nitrogen, etc. Nitrogen usage efficiency went from a pitiful 6% to 20% in rainfed pearl millet, sorghum, and maize (Prasad 2009). The 50 percent N through organics or FYM and the remaining N through inorganic fertilizer as integrated nutrient management method can be widely advocated (Vittal et al. 2002).

### 11.6.6 Use of Antitranspirants

Antitranspirants inhibit photosynthesis, and their application is restricted to preventing crop death due to extreme moisture stress. The main benefits of antitranspirants are to reduce transplantation shock especially in nurseries and horticultural crops. There are generally four types: stomatal closure (phenylmercuric acetate), reflectant (5% Kaolin spray), film forming (Mobileaf, hexadeconol, etc.), and growth retardant (Cycocel).

### 11.6.7 Crop Choice and Improved Varieties

Many conventional dryland crops do not meet with water availability due to longer crop duration. Therefore, numerous trials have been done to meet crop water requirement with rainfall and duration of water availability. A vast variety of enhanced pulses, millets, and oil seeds were examined for yield variation trend in comparison to local farmers' used varieties (All India Coordinated Research Project for Dry land Agriculture 2000). Yield improvements of 15–50% were noted by high-yielding varieties and 15–25% by more suitable crops. Adoption of short duration crops and varieties are more recommended in dryland regions to enhance crop productivity. For example, rice cultivars ZHU-11–26 in Phulbani and brown gora in Ranchi, linseed cultivar HUL-62 in Varanasi, black gram cultivar KB-51, green gram cultivar CO-5 in Kovilpatti, and soybean cultivar JS-87–59 in Rewa are also extremely sustainable in context of Indian dryland scenario (Vittal et al. 2002). Sowing at the right time helps to maximize seasonal rainfall use, lowers the incidence of pests and diseases, and provides a buffer against drought. The ideotype should have a short growth cycle, extensive root growth, fundamental dryland adaptations, and drought resistance. Apart from this can be written in place of apart from it, diversification by high-value crops like aromatic, spices, dye-yielding, medicinal plants, sericulture, and alternative land uses included to maximize returns, such as agri-horticulture, silvipasture, agroforestry, hortipasture, and other viable strategies, should come under agronomic practices for minimizing risk and maximizing return on investment in dryland environment.

### 11.6.8 Engineering Measures

Engineering measures varied spatially with respect to slope, soil type, and rainfall variation in terms of intensity, quantity, and other factors. Contour trenches, staggered trenches, contour stone walls and bunding, compartmental bunding, creating temporary and permanent check dams, gully plugging, land levelling, and other techniques are used as engineering approaches depending on these parameters.

### 11.6.9 Water Harvesting

Water harvesting is one of the viable options for excess runoff collection in a tank and utilizing it to improve agricultural output in the collected or other locations in dryland agriculture. Farm ponds (lined/unlined), percolation ponds, and silt detention tanks are the three types of collector tanks which are mainly recommended in these regions. Protective irrigation is carried out with water collection in the farm pond. Whereas, roof water harvesting also recharges the groundwater and is used for protective or supplementary irrigation by dig wells. The rainwater harvesting system basically classified into in situ moisture conservation like micro-catchment system (within field) and runoff-based system (catchment/storage) like small and macro-catchment systems (Ngigi 2003; Kushwaha and Bhardwaj 2017). They reduce runoff, promote water infiltration into soils, recharge aquifers, and help to improve local water supplies.

### 11.6.10 In Situ Water Conservation

Several technology treatments like terraces and conservation bench to improve in situ rainwater conservation have been demonstrated to be efficient in dryland regions. Technical interventions' success is determined by local biophysical and socioeconomic factors and therefore necessitates local neighbourhood action. Planting pits or zai, demilunes (half-moon-shaped moons that have been raised), earthen dividers, stone lines go along the contours, ridge tillage following the contours, etc. are also the examples of in situ rainwater harvesting techniques (Winterbottom et al. 2013).

### 11.6.11 Terraces

Terraces are built by bringing soil from the upper to lower side of a strip to form a level bench/step which has been used to control soil erosion and runoff. Because of the diversity of the landscape, they are guided by neighbourhood and local conditions when they are designing and building. Among terraces, CBTs (conservation bench terraces) also known as Zingg terraces are one of the recommended practices, where rainfall varied from 300 to 600 mm for appropriate crop production, also control erosion in addition to reduce overall runoff, and reliably boost yields (Koohafkan and Stewart 2008; Kushwaha and Yousuf 2017). But, their design should be location-specific for the most effective operation. Conservation terraces are unlikely to be effective in places with minimal rainfall (less than 300 mm) due to high installation costs.

### 11.6.12 Contour Furrow

They are similar to CBTs in concept but need less soil movement and more popularized among small/marginal farmers and/or in locations with minimal rainfall. Contour furrows at a 1- to 2-metre interval are made, and cropping is frequently done in strips or in rows. Apart from it, the excavated trench is sometimes used for runoff water collection which overflows without being damaged in severe storms.

### 11.6.13 Contour Bunds

Contour bunds are constructed with ties in the basin on a level gradient. On the bottom side of the earth bund, a stone wall is built to prevent harm if the basin is overtopped. They are also one of the more efficient SWC (soil and water conservation) measures in dryland areas.

### 11.6.14 Tied Ridges

Mechanized farming systems that use tie-ridges or furrow-diking for SWC (soil and water conservation) are proven methods. Crops are grown on contour ridges, with crossties/dykes blocking the furrows to catch rainwater for irrigation. Apart from it, they can be cultivated on the contours with any tillage strategy, including RT (reduced tillage) and no tillage. TR (Tied ridging), on the other hand, has not been widely embraced by small farmers, owing to variable yields.

### 11.6.15 Land Levelling with Lasers and Mini Benches

Laser-assisted land levelling is also very effective to overcome runoff losses. For example, this approach resulted in 20% water savings, a 30% increase in crop yields, and a 50% labour savings with 90% irrigation uniformity in the Tadla region of Morocco (Koohafkan and Stewart 2008). Minimum soil cutting and soil fertility issues connected with large volume of surface soil transfer are greatly reduced by the use of thin mini benches. They are generally built on gentle slopes of up to 2%, which is an alternative to land levelling (Jones et al. 1985). Kahlown et al. (2006) reported that technologies focus on efficient use of resource conservation like zero tillage, laser levelling, and bed and furrow planting leads to water saving of 23–45% at the same time as increasing yield in Indus basin of Pakistan.

### 11.6.16 Windbreaks and Shelterbelts

Wind breakers are any constructions that hinder wind flow and slow it down, whereas shelterbelts are rows of trees placed to protect crops from the wind. They do not totally block the wind flow. Amount of wind travels through the shelterbelts, while the rest deflect and cross over them, depending on their porosity. As a result, the wind speed is reduced without disturbance. The amount of protection provided by shelterbelts is determined by the height of the middle tree row. Shelterbelts provide protection against desiccating winds up to 30 times and 5 to 10 times their height, respectively, on the leeward and windward side. Evaporation losses are reduced as a result of the reduced wind speed, resulting in more water available for plants. During dry years, the protective impact of shelterbelts is more visible. They also help to prevent erosion from wind.

## 11.7 Irrigation Methods

India is the agricultural power house at global level in which 63% is rainfed and 37% is irrigated out of approximately 195 million-hectare (M ha) area under cultivation. India has the second largest net irrigated area, after China, but the share of water allotted for irrigation has been decreased by 10–15% in the next two decades, and average yield in irrigated and canal command area is still pathetically low. Climate change has also aggravated these problems. Presently, most of the farmers are marginal and irrigate their lands manually through conventional irrigation. In spite of its wide use, the method is characterized by poor irrigation efficiency (35–40%) which might be due to more conveyance, distribution, and application losses as well as lack of availability of reliable gadgets for water accounting and auditing at on-farm. Apart from it, most of the canal command farmers don't get timely and adequate amount of water, and tail-end farmers suffer from water shortage especially during peak season. Promoting micro-irrigation (irrigation efficiency 75–95%) and adopting advanced technologies to fulfill the dream of "more crop per drop" mantra is today's need. Enhancing land and water productivity (WP) in dryland agriculture is important not only for enhancing agricultural production on existing land with limited water availability but also for saving water for future use. It has been the subject of long-term researches, and they are well documented (Elbeltagi et al. 2021; Rockstrom and Barron 2007; Molden 2007; Bouman 2007; Kijne et al. 2003a, b). Enhancing water productivity options depends upon various factors like reducing water losses, judicious use of water resources, adopting modern agronomic practices, etc. Regarding engineering aspects, several examples described the irrigation water management effect on water productivity (Kushwaha et al. 2021; Oktem et al. 2003; Yazar et al. 2002; Kang et al. 2000; Zhang et al. 1998). Some important irrigation methods suitable to dryland regions (Fig. 11.5) are described below:

### 11.7.1 Alternate Furrow Irrigation (AFI) Method

In it, water applies in alternate furrows and reported as more efficient (25–50% water saving) as compared to the regularly utilized every furrow irrigation approach (Eba 2018; Golzardi et al. 2017; Kang et al. 2000). Many researchers also reported that

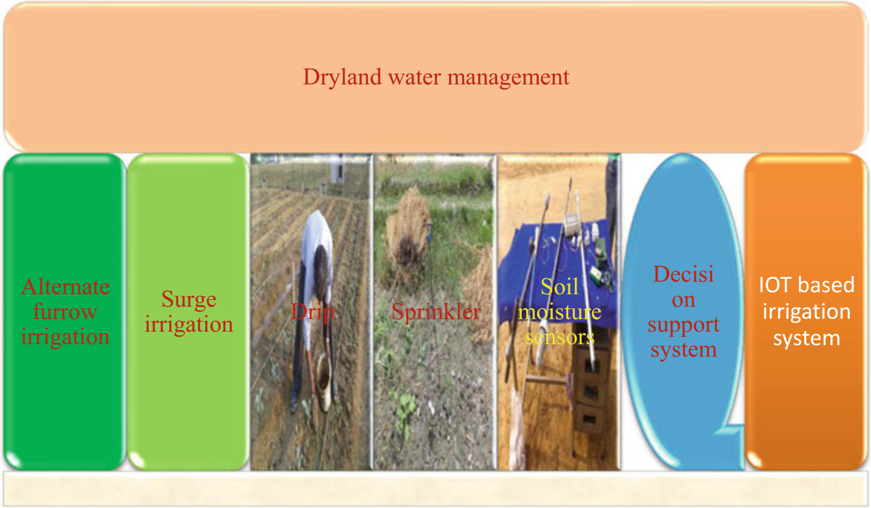

**Fig. 11.5** Options of irrigation water management in drylands

such type of strategy has enormous potential to improve crop water productivity by reducing soil water loss through evaporation (Einsenhaver and Youth 1992; Davies and Zhang 1991; Stone et al. 1982).

### 11.7.2 Surge Irrigation

Surge irrigation refers to irrigation water applied intermittently at steady or variable rates in "on" and "off" series of pulses (Bahu et al. 2005). This method works well for Vertisols because they expand and contract when wet and dried (Stringham 1988). This approach is more suitable for uniform infiltration in Vertisols led to irrigation water saving, improving irrigation efficiency (20–30%), and higher crop water productivity in addition to achieving water application efficiency up to 85% (Valipour 2013; Horst et al. 2007; Mintesinot et al. 2007).

### 11.7.3 Pressurized Irrigation System

Pressurized systems like centre pivot system, drip, sprinkler, low-energy precision application (LEPA) system, etc. are one of the most popular for effective utilization of resources like water, soil nutrients, and energy. This system has capacity to reduce the irrigation cost (20%–50%), electricity consumption (about 31%), and fertilizer saving in the range of 7–42% (PMKYS). Among them, subsurface drip irrigation is one of the effective techniques to reduce soil evaporation in context of dryland agriculture. Similarly, bucket kits of gravity-run drip irrigation are one of the low-cost viable options in vegetable garden of dryland regions. They produce vegetable as par with commercial drip systems by efficient water utilization. Sensor-based irrigation system also helps in scheduling of irrigation and enhances water use efficiency in these regions. Aside from it, it is high time to increase the use of solar energy in agriculture. Solar micro-irrigation system can play a significant role in reducing energy consumption and carbon emissions. The variable rate irrigation system enhances water efficiency by managing nutrient and water uses at the site, but in Indian dryland condition due to lack of land consolidation, such types of technologies are not feasible.

### 11.7.4 Sensor-Based Irrigation System

Sensors basically help in irrigation scheduling and automation of irrigation system. Keeping these facts, various soil moisture sensors, i.e. neutron probe, tensiometers, watermarks, granular matrix, TDR (time domain reflectometry), and FDR (frequency domain reflectometry), and canopy sensors like dendrometer, infrared thermometer, infrared gas analyser, sap flow metre, etc., have been widely used in irrigation scheduling (Fig. 11.6). They help the irrigators to take the decision regarding irrigation scheduling, but site-specific calibration is required before taking moisture content in field (Kumari et al. 2019). Wireless sensor array also helps in real-time irrigation scheduling and saves a lot of water (Vellidis et al. 2008).

### 11.7.5 Decision Support System (DSS)

Policymakers/decision-makers use DSS to solve complex problems in an improved and fast system by providing many alternatives. It also acquires real-time weather data from weather station and monitoring of soil moisture by sensor network distributed across the field via wireless communication. Various applications such as water management in various crops, yield forecasting, irrigation scheduling, computer-aided mapping, etc. have been implemented by DSS. In this context, soil-water balance softwares like CROPWAT (Smith and Martin 1991), IrriSatSMS (John et al. 2009), IrriSat (Urso et al. 2013), PILOTE (Khaledian et al. 2009), etc. help in various crop irrigation scheduling, and the DRIPD developed by Rajput and

**Fig. 11.6** Sensors for irrigation scheduling

Patel (2003) was used to determine the design criteria for a drip irrigation system. Thus, the irrigation scheme derived from DSS helps the precise application of water and supports “more crops per drop” paradigm.

### 11.7.6 IOT-Based Smart Irrigation System

This helps in automatic regulation of the irrigation system at predefined moisture content in fields from remote areas by using mobile phone which saves irrigation time and water along with farmers’ drudgery reduction (Abhilash et al. 2020). They have applied uniform moisture distribution in the farm which ultimately enhances crop water productivity even in dryland agriculture also. It also provides web-based services for collection of field sensor data, weather information, soil water status, as well as precise irrigation. It has huge potential to site-specific irrigation control even in dryland regions.

## 11.8 Economics of Deficit Irrigation Strategies

The main advantage of deficit irrigation is that the water saved from optimal irrigation may be used to irrigate more area, enhancing net income (English et al. 2002). But the accurate quantification of this economic gain is critical for future cropping and irrigation strategies. Reduced planting area, reduced water use, adoption of drought-resistant cultivars, or change in crop planning may be optimal options for increasing economic return. However, by using a good economic optimization model for irrigation and other inputs, potential income from the same land and crop type can be improved. This model primarily establishes the relationship between crop growth, water, and other inputs.

### 11.8.1 Bio-Economic Model for Deficit Irrigation

English et al. (1990) provided a simplified economic model that provides insight into the field level application of deficit irrigation and the economic gain associated with it in the context of limited inputs. Because it incorporates both land and water limitation constraints, this economic model may be applied to all places with minimal variation based on regional agricultural and climactic characteristics. Figure 11.7 depicts the analytical framework used in the basic English model.

To obtain an optimum deficit irrigation strategy, the English model and all other economic optimization models use both crop water production functions and revenue functions. Crop production functions describe the correlation between plant yield and water applied, which is not always a deliberate under-irrigation strategy (Doorenbos and Kassam 1979). It is an analytical framework for determining an optimal profit-maximizing water application level that is less than full irrigation under specified conditions. Because gross income is closely linked to crop yield, the

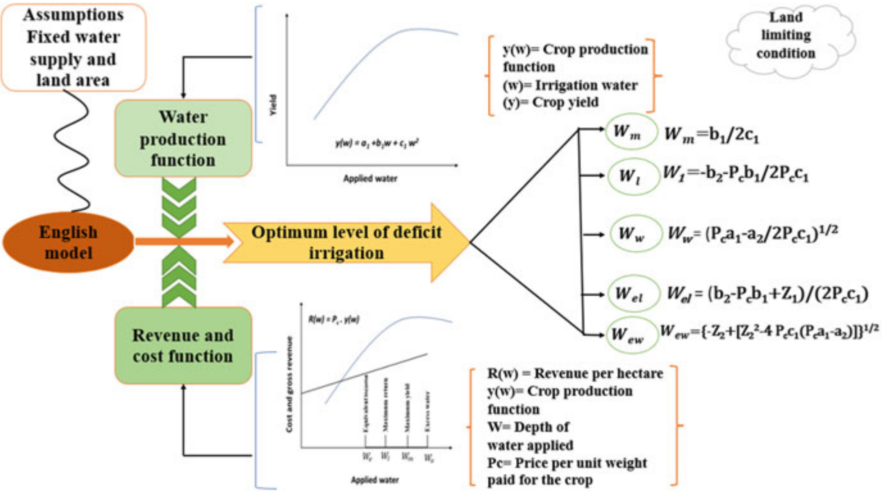

**Fig. 11.7** Analytical framework of English model for economics of deficit irrigation

revenue function will exhibit the same trend as the crop production function. This revenue function covers both fixed and variable costs incurred in farm level processes, and it is mostly influenced by regional farm input variables.

## 11.8.2 Land Limiting Condition and Opportunity Cost of Water

A bio-economic model for deficit irrigation must account for regional land and water resource limitations. Because these elements influence the plant's marginal production, the model should anticipate the optimal level of irrigation while taking into account the limiting conditions of land and water. The term "land limiting condition" refers to a non-water scarcity situation with fixed land usage. The most effective deficit irrigation approach maximizes income per unit of land. However, the opportunity cost of water is the water saved in deficit irrigation practice in the field that can be used to irrigate more farmlands, increasing overall gross income. This essentially illustrates water-limiting conditions in which we have a scarcity of water resources yet need to irrigate as much area as possible for cultivation.

## 11.8.3 Empirical Models Used in Deficit Irrigation Economics

To be sustainable, a system must strike a balance between profit and the environment in which it operates. On the one hand, it should provide the maximum benefit while without endangering natural resources such as crops, land, and water. An economic analysis gives a clear overview of any irrigation practices used in a certain set of conditions. Many researchers investigated the economic benefit of deficit irrigation

**Table 11.2** Various types of methods used for economics of deficit irrigation

| S. no. | Types of empirical economic models | | References |
|---|---|---|---|
| 1. | Programming model | Normative model | Ali et al. (2017); Doppler et al. (2002) |
| | | Linear programming model | Bartolini et al. (2007); Galko and Jayet (2011); Hazell and Norton (1986) |
| | | Positive mathematical programming model | Heckelei and Wolff (2003); Howitt (1995); Merel et al. (2011) |
| 2. | Econometrics model | | Hendricks and Peterson (2012); Moore et al. (1994) |
| 3. | Field experiments | | Bouarfa et al. (2011); Cusicanqui et al. (2013); Maestre-Valero et al. (2016) |
| 4. | Hedonic pricing | | Campos et al. (2021); Joshi et al. (2017); Kakhki et al. (2010) |
| 5. | Contingent valuation | | Mezgebo et al. (2013); Storm et al. (2011); Weldesilassie et al. (2009) |

by using various approaches and bio-economic models to assess its long-term viability in crop yield and farmer profitability. Table 11.2 shows the various approaches used for deficit irrigation economics.

## 11.9 Conclusion and Outlook

Being able to provide food and fibre for the world's population has become a conundrum amidst freshwater scarcity especially in arid and semiarid region. The dryland areas (i.e. 41% of the global terrestrial) are dominated for grazing and rainfed cropping because of water scarcity, and the crop water productivity generally remains low due to on-farm water losses through seepage and evaporation. In water-short areas, irrigation water supplies remain abundant, and efforts are to maximize crop productivity and may be done through on-demand irrigation service. This will help to meet the full crop demand with negligible deep percolation losses. Stressing crops enhances water usage efficiency, without hampering the yields. Under such conditions in the dryland farming system, sustainable crop production may be achieved by employing deficit irrigation (DI) techniques. Deficit irrigation with scheduling reduces irrigation water consumption and conserves available water resources.

This chapter presents detailed discussion on improving water productivity through deficit irrigation in conjunction with irrigation scheduling and management practices such as mulching, tillage, mixed cropping or crop ration, and nutrient management. Major water saving from the irrigation system is the future need, and that could be achieved by precise management and innovative design for water delivery and field irrigation. Previous study showed that deficit irrigation has potential for sustainable reducing in agricultural water use. Present chapter could provide information that contributes in improving crop water productivity in high water-competitive environment. In conclusion, the adoption of DI may be promising in areas where available soil moisture for crop is limited and adequate land is available.

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# Meta-Analysis Studies Emphasizing Activities Related to Natural Resources Management for Imparting Resilience to Dryland Agriculture

# 12

Mangshatabam Annie and Raj Kumar Pal

**Abstract**

More than 41% of the world area is covered by dryland (arid and semiarid) ecosystems, which provide habitant to 2.5 billion people. India occupied more than half of South Asia dryland habitats. Forty percent of the world total grain production and nearly two-thirds of all livestock are supported by dry land, which generate about. Despite playing such crucial roles, dryland agricultural production systems face various obstacles that jeopardize their adaptability and long-term viability. The need of the hour for improving the future of dryland ecosystem is to identify the key challenges and issues on which system research should concentrate and the major strategies for enhancing dryland agroecosystems. This will result in a more resilient and sustainable agricultural production system.

**Keywords**

Dryland · Challenges · Resilient · Sustainable agriculture

## 12.1 Introduction

Cultivating of crops only with natural rainfall and without the use of irrigation is known as dryland agriculture. Dryland agriculture is characterized by low, erratic rainfall and a lack of dependable irrigation systems. Majority of the coarse grain crops, pulses, oilseeds, and raw cotton are farmed on these lands, making dryland agriculture key to the economy. The Fourth Five-Year Plan of India defines dry lands

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as regions with very little irrigation infrastructure and rainfall between 375 mm and 1125 mm. Dry lands have a very unstable economy and highly vulnerable to environmental stress and shocks. Agricultural yields and additional land degradation are caused by degraded soils having lower water holding capabilities, several nutrient deficiencies, and a decreasing ground water table.

The greatest risk to worldwide food security and sustainable development is climate change. Augmented occurrence in incidence of extreme climatic measures like cold wave conditions, cyclones, heat wave, as well as frost and hailstorm over short periods employs adverse impact on harvest of crop (Prasad et al. 2014). Moreover, the regularity of existence of extreme weather measures, i.e., tropical cyclones as well as heat waves, is increasing, which significantly affect farming system. It is true that a number of additional characteristics, i.e., biotic and abiotic factor, such as water availability, diminishing soil quality, as well as pest and disease infestations, are having an impact on dry lands globally, in addition to the imminent effects of climate change. Dryland agricultural productivity can only be raised if the issues are clearly understood and properly addressed. Here, it is stressed how important sustainable natural resource management (SNRM) is for resolving problems in these regions. Research and development must take a multidisciplinary and comprehensive approach in order to enhance crop yield and profitability without risking the long-term viability of local agricultural systems if dryland agriculture is to remain profitable during the next century.

Thus, for strengthening dryland agroecosystems, the following will be the key component (SNRM) for providing resilience to dryland agriculture:

- Environment (soil, water, temperature, pests, and pathogens).
- Management (crop rotation, tillage, watershed management, rainwater harvesting).
- Genotypes (improved variety, resilience, crop diversification).
- Social economics (public policy, information, regulations).
- Technology (GIS, remote sensing, crop modelling).

## 12.2 Main Dryland Agricultural Areas Worldwide

More than 2.5 billion people throughout the world depend on dryland (arid and semiarid) environments for their survival, and these habitats are also the origin and diversification hubs for many domesticated and wild plant and animal species. Nearly 40% of the world area is covered by arid and semiarid regions, which are home to 700 million people and rainfed farmland. About 97 million ha (68%) of India projected 143 million ha net cultivated land is dry land/ rain fed, providing 40% of the country's food needs while supporting 40% of humans and 60% of livestock populations. According to physiography, in India, dryland agriculture is practiced in the desert regions of Rajasthan in the northwest; Central India plateau; the Ganga-Yamuna River Basin alluvial plains; Gujarat, Maharashtra, and Madhya Pradesh Central Highlands; Maharashtra rain-shadow Deccan region; Andhra Pradesh Deccan Plateau; and Tamil Nadu highlands. A substantial part of dryland agricultural production systems has undergone changes related to population and climate, most frequently with a variety of negative environmental effects, in an effort to satisfy the livelihood goals of the continuously expanding human population (Singh, 2000).

## 12.3 Keys Challenges and Issues in Dryland Agriculture

South Asia has a wide range of climates, from the warm, humid, and subhumid tropical climates that predominate in the region southern and easternmost parts to the semiarid and arid subtropical regions of western India and Pakistan. Particularly in India, where rainfall is more variable, these regions are among the riskiest for rainfed agriculture. Several nutritional deficits, frequent droughts, soil degradation, low organic content of soil, low levels of external inputs, low investment capacity, and weak market networks are the main obstacles to rainfed agriculture (Rao et al. 2015). Additionally, the available agricultural possibilities in these areas rely on the current socioeconomic circumstances. In developing and undeveloped countries, a number of challenges are being faced including a depleting natural resource base, climate change, food poverty, and nutritional insecurity, among others. Any enhancement or adjustment to these problems may result in a change. Production of dryland crops is hampered by both biophysical and socioeconomic factors. Low, uneven, and inconsistent rainfall is the main barrier to the yield of dryland crops. Rainfall cannot be changed; thus, the only alternative is to control its impacts in order to maximize their effectiveness and minimize any potential negative consequences on dryland environment.

### 12.3.1 Declining Natural Resources Management

The main obstacles to increasing dryland agriculture productivity are soil and water shortage, which is made worse by environmental degradation and soil deterioration. Demands on soil, water, vegetation, and other natural resources have increased as a result of high population densities and rapid population expansion. Approximately 70% of Indians reside in rural regions, and the majority rely for rainfed farming as well as vulnerable woodlands for their livings. In India, the amount of water availability annually has been reduced from 5177 $m^3$ in 1951 to 1654 $m^3$ in 2007 (MOWR 2008). Fifteen percent of districts, according to the Central Ground Water Board, are overexploited and rising at a pace of 5.5% annually (Rejani et al. 2015). Between 1981 and 2000, the groundwater level in 16 Indian states decreased by more than 4 m, with northwestern India experiencing the most. In numerous regions of states of Gujarat as well as Rajasthan, the groundwater status diminished by more than 16 m.

Widespread degradation of natural resources, including drying of wetlands, is occurring; drought exacerbates the issue brought on by poor management of river basins, irrigation schemes, and dams. Water potentials are scarce due to soil degradation, irrigation, and the expansion of sand dunes into towns, farms, and on roadways. Due to deforestation and vegetation loss, which reduced the land ability to retain water, floods have dramatically increased in recent years. In rainfed agriculture, soils are crucial for productivity and resistance to climatic calamities like drought. Potential barriers to increasing productivity in these areas include the deterioration of productive soil by erosion, the reduction of soil carbon-based organic substance, the appearance of secondary and micronutrient shortages, soil compaction, surface crusting, as well as the deterioration of soil biodiversity.

### 12.3.2 Climate Change Scenario in Dryland Agriculture

It is firmly believed that climate change will make dryland agriculture issues even worse. Recently in India, heat waves have lasted noticeably longer and have occasionally been very severe. Also, in many parts of the globe, frequency of extreme rainfall events has generally increased, leading to major floods, drought, and extreme cyclone. Northern part of India is projected to experience warmer day. The effects of climate change will be amplified when added to the well-known harmful effects of drought on dryland farming regions around the world. If not successfully addressed, this will inevitably lead to a sharp decline in the yield of food grains. Planning for sustainable development in the area needs to incorporate climate-resilient techniques for adaptation to climate change. This procedure would be made easier with a better understanding of the effects, vulnerabilities, and adaption strategies associated with climate change. By the 2080s, the IPCC projected climate change for India, and it is been expected that temperature and rainfall will change by a range of 0.87 °C to 6.31 °C and − 24.83% to +15.18%, respectively (Lal et al. 2001).

### 12.3.3 Socioeconomic Issues

The ultimate aim of all development initiatives is to raise socioeconomic conditions and consequently human welfare. All policy actions must acknowledge addressing food security goal, poverty, and nutrition, but certain aspects of the current socioeconomic environment can make this goal more difficult to achieve. Population pressure and smaller farm sizes are two examples of these aspects in dryland ecosystem. Another factor that determines socioeconomic situations is the lack of hard and soft infrastructure. At the regional level, lack of political trust also leads to ineffective policymaking, which is shown in the sluggish execution or poor adherence to a number of regional accords.

The effects of climate change on dry lands in sub-Saharan Africa are significant. Food security, health, and water supply in the area are seriously threatened by increasing temperatures, shifting precipitation patterns, and degrading soil. The increased level of livelihood insecurity may then lead to migration as a stress-reduction or adaptation strategy. A meta-analysis which is based on 89 original case studies examines the relationship between environmental change, adaptability, and migration in rural sub-Saharan dry land. The study concluded that migration can be utilized in conjunction with in situ measures for diversifying income and changing agricultural practices, or it can be used as a last resort strategy for extremely vulnerable people. The above findings have significant implications for understanding environmental migration by emphasizing the importance of local factors and complementing types of coping and adaptation (Hoffmann et al. 2022).

The importance of dry lands in decision-making may be raised through the monetary pricing of their ecosystem services. However, a thorough evaluation of the metrics used to calculate the projected monetary values for dryland ecosystem services is lacking. Schild et al. (2018) developed a database of 559 observations from 66 valuation studies in dry lands around the world and used multiple regression analysis to assess the relative weight of local socioeconomic, environmental, and methodological indicators in explaining the estimated monetary values for nine dryland ecosystem services. The findings demonstrate that local socioeconomic and environmental factors only have a minor impact on dryland value, indicating that existing valuation methodologies do not adequately account for local dryland conditions. This underlines the necessity of improving monetary valuation techniques so that they more accurately reflect local dryland conditions in order to be useful as a tool for decision-making.

Participation of local communities, integration of conventional ecological facts and practices, consideration of local people’s short- and long-term needs and value systems, clarity in task and benefit allocation, and strengthening of local organizations are essential not merely for cost-sharing but also for the long-term success of dryland rehabilitation initiatives.

## 12.4 Opportunities for Dryland Agriculture Resilience

For the majority of the countries, eradicating poverty, enhancing nutrition, and ensuring access to safe food are of utmost importance. A renewed focus is being placed on using agriculture for development and fighting hunger and poverty. Aside from providing a means out of poverty, agricultural expansion also encourages employment in non-farm rural enterprises and makes it easier for people to migrate to non-agricultural paths without experiencing hardship. Based on this, it is believed that expanding agriculture and overall rural development are necessary for a long-term reduction in poverty. Increased income for the poor and lower food prices are two ways that agricultural growth contributes to a reduction in hunger and poverty. Numerous factors, including input and product prices as well as non-price factors, influence the growth of output and farm revenue. A profitable price for production, access to more advanced technology, the utilization of high-quality inputs, and the usage of contemporary equipment are all necessary for increasing growth. Dryland farming has enormous potential to increase agricultural output. To boost farm productivity and profitability, it is essential to manage resources well in order to realize the potential of rainfed agriculture. Management of the soil and water will be essential.

### 12.4.1 Technological Approaches

The main force behind agricultural progress is technology. The genetic augmentation of productivity should be combined with input-use efficiency in light of the prices and limitations of resources like water, fertilizers, and energy. Agricultural research systems have created some innovative technologies that hold promise for removing obstacles, identifying the requirements of farmers for rapid expansion, and supporting farming practices that will enhance the availability of natural resources, thus aiming to increase climate change resilience and aid in mitigation and current development strategies. This is a clear indication of the potential to increase productivity through the successful spread of agricultural technologies. High input levels and advanced management could result in yield increases of two to five times. In regions like SAT, specialized dryland management techniques such as water harvesting and decreasing soil moisture loss can boost crop outcomes by an additional 5–15% on average and lower yield fluctuation from year to year, resulting in a more consistent production (Fischer et al. 2010).

### 12.4.2 Efficient Soil, Water, and Nutrient Management

In dryland agriculture, soil, water, and nutrient management are interwined. To combat water scarcity during crop season, integrated soil and water management is crucial. This involves on-farm water storing, water harvesting, water shed approach, and also agronomic methods to maintain soil moisture for the crop to give maximum yield. Other significant efforts that also need to be carried out include combined management of river basins, flood plains, aquifers, as well as their related vegetation for the purpose of providing water storage and flood regulation services. Watershed management in dry lands is one of the most important technological interventions in order to manage natural resources. A watershed is well-defined as any geographic part from which rainwater or irrigation water is stored as well as exhausted over a common point, serving as a construction to store water for later use.

In order to alleviate drought or moderate flooding, prevent soil erosion, increase water availability, and ultimately increase food, fodder, fuel, and fiber on a sustainable basis, watershed management, rainwater harvesting, and water use efficiency carried out a wise use of all the natural resources available, including terrestrial, aquatic, and vegetation cover. Watershed management entails the treatment of land using the best biological and engineering practices in order to save rainwater as much as possible on-site and store the excess in ponds or check dams for ground water recharge. Further, most of the success of technology will also depend on how the land is used according to its potential and with also on preserving soil nutrient.

With the help of watersheds, marginal areas can be used effectively. Water saving can be done to provide additional irrigation during dry spells and at crucial stages of crop growth, such as anthesis and grain filling. In a detailed review of 311 meta-analyses of studies on watershed interventions in India to study efficiency, equality, and sustainability advantages, it was found that the watershed projects increased irrigated area, created a lot of employment possibilities, and were most effective where cropping intensity was targeted and soil and water resources were protected. The study found that rainfed areas are being quietly revitalized and revolutionized by the watershed initiative (Joshi 2005). As a result, it turned out to be more clear that water management in favor of rainfed agriculture needs a landscape perspective as well as engages cross-scale interaction spanning from farm residence scale to watershed/catchment scale and upstream-downstream linkages.

For the production of agricultural goods, water is a limited natural resource. Although it is widely acknowledged that different crop types have different water use efficiency (WUE). Mbava et al. (2020) Utilizing meta-analyses data a detailed studies was carried from 514 experiments conducted worldwide, the impacts of rainfall pattern, soil type, and climate regime on crop WUE were assessed. According to the data, crop type significantly affected WUE, with cereals providing an average of 2.37 kg of dry grain per cubic meter of water ($m^3$), followed by oilseeds (0.69 kg $m^3$), fiber crops (0.45 kg $m^3$), and legumes (0.42 kg $m^3$). Sorghum (2.52 kg $m^3$) and maize (3.78 kg $m^3$), among cereals, used less water than wheat (1.02 kg $m^3$), barley (1.21 kg $m^3$), and millet (0.47 kg $m^3$). Through subtropical environment, WUE of crops grew from the desert to the tropics. These findings offer data that are crucial for crop selection in the face of increased climate unpredictability and for the development of crop varieties with improved WUE.

Based on meta-analysis research, Garba et al. (2022) evaluated the effects of cover crops on soil water and soil mineral nitrogen content during seeding of future cash crops and their yields compared to control fallows. Thirty-eight articles covering independent investigations on 1006 cash crop output, 539 soil water, and 516 soil mineral nitrogen from 1994 to 2021 in total were examined. With considerable variations among climates, soil types, and crop management practices, cover crops lowered cash crop output on average by 7%, soil water content by 18%, and soil mineral nitrogen by 25%. According to the study findings, in dryland conditions, a minimal amount of yearly precipitation of 700 mm serves as a “breakeven” point for cover cropping to significantly increase cash crop yields when compared to control fallows.

### 12.4.3 Improved Agronomic Practices

Agronomic and crop management practices like growing short-duration or early-maturing, photo-insensitive, as well as more tillering cultivars through optimal root traits, accepting to abiotic as well as biotic burdens, covering with crop residues, establishing more seedling per hill for heat stress, improving soil fertility as well as managing water, and moisture preservation for delayed onset of monsoon modification of fixing dates of sowing to diminish the consequence of high temperature increase-induced spikelet sterility might be used to decrease outcome variability, through avoiding crop flowering to coincide with the heat stress period. Altering the cropping calendar to take advantage of the wet period and preventing extreme weather events during the growing season are two adaptation methods that may be used to lessen the negative consequences of increased climatic variability, which is typically observed in arid and semiarid tropics. When the crop is in its critical period of growth, crop varieties that are resistant to lodging may sustain severe winds. Improved crop management, including intercropping and crop rotation, integrated pest control, and agroforestry and afforestation programs, will also be a key part of dryland strategic adaptation to climate change. As varied plant germination mechanisms serve as a buffer against inter-annual fluctuation in growth circumstances, this will also aid in the dynamics of plant communities. Identification of climate resilient crops and cultivars for various locations is necessary for dryland agriculture to properly adapt to climatic changes and unpredictability. Dryland agriculture will be able to adapt to climate change with the help of information as well as understanding of photoperiod sensitiveness, data on the genetic disparity for transpiration effectiveness, short-duration varieties that evade the terminal drought, as well as high-yielding, disease-resistant varieties.

Ridges as well as furrows are developed that function as a continuous barrier to the free flow of water downward, extending the time for infiltration. As a result, the withdrawal of soil and nutrients is more tightly controlled, increasing soil fertility and crop output. One of the many in situ soil and water conservation techniques for black and red soils is ridges and furrows, which can enhance crop yields by up to 15%.

Ridge-furrow cultivation (RF) is a well-liked dryland agricultural technique that is practiced in many parts of the world. Based on the meta-analysis conducted by Wang et al. (2020) on ridge and furrow effects on maize yield, ET, and WUE in China, they have observed that ridge and furrow boosted maize yield and WUE by 47% and 39%, respectively, on average, across all geographic regions, but had little impact on ET. Under RF, yield and WUE increased in all regions, regardless of the mean growing season air temperature (MT) or the mean growing season precipitation (MP). In areas where soil bulk density (BD) was low (1.3 g $cm^3$), RF boosted yield, ET, and WUE. However, RF only boosted the yield and WUE in regions where BD is greater than 1.3 g $cm^3$. No matter whether mulching was utilized or not, RF boosted yield and WUE while lowering ET. Combining RF impacts on yield, ET, and WUE in maize, environmental factors and management techniques were crucial for optimizing these effects.

Through the preservation of soil and water resources and other associated ecological advantages, conservation agriculture is being marketed as a technique for both mitigating and adapting to climate change. Zero/minimal tillage, soil cover from crop residues or cover crops, and appropriate crop rotations are the main components of conservation agriculture. To increase soil fertility and provide food on a small amount of land, conservation agriculture uses crop rotations, reduced tillage, and permanent soil cover. Yield Variability was measured in this case using stability analysis. Considering the specifics of maize grain yield meta-analysis data on maize, grain yields were gathered from extensive research (>5 years) on tillage and crop residue management in semiarid and subhumid environments conducted around the world (Rusinamhodzi et al. 2011). From the study, it was found that there was a significant correlation between annual rainfall and maize grain yield in Southern Africa.

Results suggest that using conservation agricultural techniques like rotation and high input utilization in low-rainfall locations increases maize production over time. However, there was no difference in the stability of the system under those circumstances. We found a significant correlation between annual rainfall and maize grain yield. The outcomes of meta-analysis concluded that (1) 92% of the data illustrate that mulch cover makes lower crop output due to water logging in high rainfall areas. (2) Eighty-five percent of the data show that soil texture is significant in the temporal enlargement of conservation agriculture effects, with greater yields likely on well-drained soils. (3) According to 73% of the data, conservation agricultural strategies demand substantial inputs, particularly nitrogen, to improve yield. (4) According to 63% of the data, rotation increases yields; however, estimates frequently omit fluctuations in rainfall within and between seasons. In semiarid regions, less tillage without mulch cover results in lower yields, according to 56% of the data when appropriate fertilizer is available, rainfall is the main factor affecting yield in southern Africa. Thus, the findings make it abundantly evident that for greater impact, conservation agriculture must be aimed at certain biophysical circumstances.

Significant water savings are needed for dryland crop production, although many dryland regions have experienced issues with irrigation (e.g., China, Australia, and the Mediterranean basin). Increasing water use efficiency is an important tactic for maintaining crop yields without overusing the limited water supply (WUE). One of the tactic for improving WUE is by the use of plastic mulch, and it is also considered as a promising strategy for dryland cropping systems. In China, plastic mulching technology for wheat and maize is widely employed. Daryanto et al. (2017) quantitatively compared the effectiveness of plastic mulching to conventional irrigation in the same location using a meta-analysis approach. Peer-reviewed journal articles released in English between 1985 and 2016 were used as the source. According to their research, plastic mulch increased yields comparable to those of irrigated crops while using 24% less water than irrigation, principally due to a much higher WUE and greater soil water retention. Rainwater was diverted into a very small planting zone by covering the ridges in plastic and directing it there (furrow). Evapotranspiration (ET) is the main eco-hydrologic activity in dry lands. Due to this, it is crucial but difficult to partition ET by establishing the relative importance of interception (I), soil evaporation (E), and plant transpiration (T). Recently, however, there has been an increase in in situ investigations aimed at quantifying T/ET due to advancements in measurement methods and data accessibility.

Sun et al. (2019) conducted a detailed meta-analysis on evapotranspiration partitioning in dryland ecosystems in which 38 datasets were drawn from 31 studies in dry land all over the world. The analysis concluded that (1) there was no connection between factors influencing fluctuations in transpiration/evapotranspiration and yearly precipitation, soil texture, or ecosystem type, (2) fractional cover is not as essential a regulating factor as leaf area index, and (3) T/ET varies most during dynamic wetting-drying events. It was also demonstrated that several factors governed evaporation and transpiration. Additionally, when interception and shallow groundwater are prominent, taking these characteristics into consideration is essential for accurate T/ET quantification.

### 12.4.4 Breeding and Genetic Resources for Abiotic Stress

The most crucial and economically advantageous elementary raw substance that will enable agriculture to acclimate to climate change may turn out to be genetic resources. In order to ensure that the desired varieties are accessible when the consequences of climate change are constantly felt, it is imperative to begin breeding significant crops geared at reducing climate stress through qualities like temperature as well as drought tolerance and high yield. For some time, plant breeders have been concentrating on high water usage efficiency as a means of increasing agricultural productivity in water-strapped areas. Plant breeders have been focusing on high water usage efficiency for some time now as a strategy to boost agricultural productivity in water-restricted areas. Establishing seed banks is critical in conditions with great variability and unpredictability. This will offer a useful way to rebuild crops destroyed by significant catastrophes and extreme weather events. To make use of all the water acquired, it is crucial to address additional issues that impede crop development in addition to rainfall loss issues. Choosing the appropriate crops to lessen the strain on food security and water resources in dryland agricultural regions and ranking high-yield crops according to how effectively and sustainably they use water resources under drought stress are two of the numerous examples of land management practices in dryland ecosystem that may improve water use efficiency.

Evaluation of water-use efficiency (WUE) conducted a worldwide meta-analysis of 40 crop species under drought stress circumstances across varied habitats that included 907 experimental observations from 96 research publications. The findings demonstrated that drought stress considerably reduced crop WUE by an average of 2.8% when compared to well-watered settings, but the impacts differed among crop species. Four factor drought intensity being the most significant (32.9%), followed by type of weather (23.5%), soil texture (20.2%), and crop type (17.1%), could account for the majority (93.6%) of the variance in crop WUE. This study identifies variables that determine how well crops respond to drought and suggests high-yield crop choices that can cope with drought in dry lands.

### 12.4.5 Use of GIS and Remote Sensing and Simulation Models for Identifying the Constraints and Yield-Gap Analysis

By using remotely sensed data to GIS and simulation software, it is possible to create strategies for managing the natural resources in the watersheds effectively and sustainably. Regular satellite-based multispectral observations have the enormous potential to deliver crop information quickly and affordably. They also make it possible to examine dynamic phenomena and gauge the success of watershed remediation effort of dryland agriculture. Maintaining canopy cover and soil cover is crucial for dryland agriculture in particular to prevent temperatures from rising and causing soil moisture to evaporate. The impact of vegetation on temperature increases on an agricultural scale merits investigation. Remote sensing vegetation index like NDVI/EVI can be used as a measure to determine whether there is drought and to track vegetation development. Because of the effects of changing seasons and land usage, a lack of water availability results in a decrease in vegetation. Drought and higher soil surface temperatures are impacted by these circumstances. The production of agriculture will be impacted by temperature rise over time.

Crop simulation models are useful for assessing how well technologies operate in various agroclimatic conditions as well as for identifying the key obstacles to productivity maintenance and finding the right application domains for technologies. In an integrated watershed management strategy, crop growth simulation models offer the chance to simulate crop yields in a specific climatic and soil condition.

### 12.4.6 Policies that Need to be Adopted

- Without substantial public investment, the potential of genetic modification and other productivity enhancing technologies cannot be fulfilled, particularly in the area of natural resource management.
- Creation of site-specific technology for livestock, agricultural production, range management, moisture conservation, soil management, and agroforestry.
- Dissemination to end users of appropriate agricultural technologies and providing sufficient agricultural financing, as well as supplying farm equipment and inputs (such as high-quality seeds, fertilizers, etc.).
- Proper implementation of a successful price support scheme for particular dryland crop products.
- Consolidation of scattered holdings on land in arid areas to help farmers manage their farms more effectively.

## 12.5 Conclusions and Future Directions

Dryland farming will continue to be crucial in maintaining livelihoods and ensuring food security, especially in developing nations. The ability to bounce back from negative climate change consequences must be permanently retained in order to be considered resilient in dryland ecosystem. Dryland areas are the world's hotspots for water, food, and livelihoods. In order to achieve potential levels of arable land and water productivity, it will be necessary to refine technology and deploy cost-effective solutions in a timely manner. This will increase agricultural productivity using the existing water resources. Adopting a comprehensive strategy for dryland farming that integrates site-specific nutrient management at the watershed or catchment level with soil and water conservation methods is urgently needed in order to boost agricultural production and sustainability.

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# Part III

# Improving Sustainability of Dryland Farming System by Improving Reliability and Resilience

# Soil Organic Carbon Sequestration in Dryland Soils to Alleviate Impacts of Climate Change

## 13

Shidayaichenbi Devi and Shubham Singh

### Abstract

Dryland region covers 47.2% of the global area. In India, it covers 68% of the total cultivated area and supports 44% of the world's food production for the ever-increasing population. However, the global warming into climate change due to anthropogenic activities adding carbon compounds such as carbon dioxide, methane, carbon monoxide, etc., into the atmosphere, the soil health has deteriorated and reduced the production potential of the region even in irrigated conditions, owing to the higher mineralization rate of organic matter content as compared with the addition or accumulation of it due to an increase in temperature under global warming. The soil without organic matter cannot support plants to grow in there and in turn, the plants are the source of the organic matter. The development of a vegetative environment under climate change in the regions, especially in arid regions, is questionable, whether possible or not; if possible, how long will it take; and within that time the livelihood will be able to be sustained or not. It is also expected that dryland areas will keep on increasing due to global warming. To urgently combat the increase of this area and the reduction of global warming, addition of organic matter such as farmyard manure (FYM), vermicompost, green manure, microbial consortia, plantation, regular irrigation, etc. was introduced, which can help sequester atmospheric carbon dioxide through plants called "carbon sequestration." Plants require it for their photosynthetic process with sunlight and water. More the sequestration of atmospheric carbon and retention in the soil by way of plants increases the soil organic matter into soil organic carbon content when decomposition of the plant materials and

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enhances the soil health and helps in reducing global warming. Making it possible for just a plant to grow in the dryland soil without any hampering its growth and development is the only solution for alleviating climate change.

**Keywords**

Dryland · Global warming · Anthropogenic activities · Carbon sequestration · Climate change

## 13.1 Introduction

Dryland regions cover almost half of the global areas including grassland, agricultural land, forest land, and desert land depending on the soil moisture availability and climatic variations. Due to industrialization and the population pressure on the lands, the utilization of marginal lands is expanding, and the dry lands are under the target for crop productivity. However, the dry lands have atmospheric and hydrospheric constraints, which limit the growth of plants. Besides, the continuous emission of greenhouse gases (GHGs), adding carbon compounds such as carbon dioxide ($CO_2$), methane (CH4), carbon monoxide (CO), etc., by anthropogenic activities like combustion of fossil fuels (natural gas, petroleum, crude oil, etc.), deforestation, land degradation, etc., to the atmosphere causes global warming (GW). It is reported that 1 °C of surface temperature rises from 1901 to 2020 (Lindsey and Dahlman 2020), owing to the release of $CO_2$ into the lower layer of the atmosphere (troposphere). The present concentration of atmospheric CO2 is 414 ppm by 2020, which was once 280 ppm before industrialization (eighteenth century). This elevated temperature causes climate change affecting the global cycles between the atmosphere, hydrosphere, and lithosphere. The dry lands have a lower content of soil organic matter (SOM) of less than 0.5% by weight. With the temperature rise, the mineralization of SOM into soil organic carbon (SOC) increases and again declines the content when less addition of the sources. The dry lands have less favorable vegetation and livestock/grazers, which are the sources of SOC content. In present days, the increment of declining SOC content in dry lands could be the reason for climate change, and this region again can be a solution for mitigating climate change as it has potential. The mitigation can be through carbon sequestration, which is the trapping of atmospheric $CO_2$ inducing greenhouse effects (GHEs) by plants needing for their photosynthetic process with water and sunlight. The growing of more plants in the dry lands could be a solution for controlling the atmospheric $CO_2$ level with the accumulation of SOM in soil into SOC as stock for years. This is how plants can mitigate climate change with the improvement of soil properties such as physicochemical and biological properties. However, the introduction of a plant to grow in the dry lands is not an easy task because of the limited availability of the plant's growth necessities. The application of organic inputs can initiate for ensuring the existence of soil microbes for decomposition and mineralization processes for plant nutrient availability and with regular moisture supplied. Once soil microbes are involved in soil functions, the soil properties are enhanced and increase the plant's growth. The growing of plants, presence of soil microbes, application of organic inputs, and SOC stocks are inter-linked and act as a close system. The accumulation of SOC and remaining in the soil for years is the approach for controlling the atmospheric temperature rise. The management strategies for maximum storing of SOC with enhancing soil health and crop productivity are a way of mitigating climate change. Only the developing countries face issues with management practices. Government should take initiative for strengthening the socioeconomic status of the farmers thereby atmospheric carbon (C) being managed in the soil.

## 13.2 Need for Carbon Sequestration in Dryland Regions

Dryland regions are the prime part of the global system in terms of in-use area, ecology, and socioeconomic aspects. The region is denoted by low precipitation, elevated temperature, prone to soil erosion, low SOM content, stricken soil biodiversity, less diversified vegetation and livestock, and social and economic barriers, thereby leading to desertification due to soil degradation. However, the region occupies a large global area, i.e., 6.2 Bha (billion hectares) or 43.2% of the global land area, and a hoped-for 44.2% by 2050 due to climate change (Lal 2004; FAO 2020). India has nine states under dryland regions where Andhra Pradesh, Chhattisgarh, Tamil Nadu, Rajasthan, Madhya Pradesh, Gujarat, Jharkhand, and Karnataka cover 80% of the total dryland areas. It can be managed and has the potential for sequestering the maximum atmospheric $CO_2$ as global C stocks in surface and sub-surface ground biomass systems through plants called "carbon sequestration" into SOC stocks. The total SOC content in the dryland soil is about 241 Pg (1 Penta gram = 1015) (Eswaran et al. 2000), and the contribution of C to the troposphere through anthropogenic activities is 40 times less than that, approximated as 6.3 Pg carbon/year in the 1990s (IPCC 2001; Schimel et al. 2001). This stock of SOC can be accumulated for a long run in soil due to shortage of water and elevated temperature for mineralization, thereby helping in the mitigation. Dry land's constraint and their importance on carbon sequestration are discussed below.

### 13.2.1 Precipitation on Carbon Sequestration

Precipitation includes rainfall, fog, drizzle, snow, etc., in which rainfall is less than 750 mm and the other forms are very rare in dryland regions. It is the most limiting factor in the region, so the content of SOC is generally less. In India, it varies from 0.1 to 0.4%, depending on the clay content of the soils (Balpande et al. 1996). Based on the availability of moisture as aridity index (AI), dry lands are subtyped as subhumid (dry) ($0.5 \leq$ AI $\leq 0.65$), semiarid ($0.2 \leq$ AI $\leq 0.5$), arid ($0.05 \leq$ AI $\leq 0.2$), and hyper-arid (AI $<0.05$) (Middleton and Thomas 1997). The hyper-arid areas are the desert regions where cultivation is impossible and prone to heavy wind erosion of soils. The increment in the amount of rainfall distribution per annum can sequester more atmospheric $CO_2$ through plants. Activities such as recovering degraded areas, reforestation, afforestation, forestation, improved agricultural activities, and revegetation can increase the precipitation rate and regularize the rainfall pattern. Because a dense vegetation can affect the sun's albedo by absorbing more heat and then warming the soils, which evaporate the moisture to the atmosphere where it condenses and rain. Regions where an adequate amount of moisture availability is prone to density vegetations with the addition of SOC stocks through carbon sequestration.

### 13.2.2 Temperature on Carbon Sequestration

Climate change influences the soil temperature as it functions as the flux and exchange of heat between the soil and atmosphere. The increment in the atmospheric temperature due to the GHGs effect increases soil temperature, which controls the soil physicochemical and biological properties that affect the plant's growth (Buchan 2000). Increased solar radiation trapped and received by the soil affects the soil temperature regime. It is a crucial factor since optimal warmth at the required depth is efficient for plant growth. It, moreover, determines the time of sowing, and the optimum temperature is between 5 and 35 °C for plant to grow. A temperature below 5 °C cannot germinate the seeds and above 35 °C hampers the metabolic activities of plants and then their growth. Mostly, the dryland regions experience higher temperatures, above the optimum level, and keep on increasing due to climate change enhancing the soil and plant's evapotranspiration rate and reducing the plant's productivity, which ultimately accumulates less amount of SOC content (Herold et al. 2014; Martin et al. 2010). With the increment in soil temperature, the activities of soil microorganisms are enhanced and the supply of SOC also increased (Mao et al. 2015). However, due to dryland constraints for plant growth, the SOC accumulation is minimum. The plantation can maintain the atmospheric and soil temperatures by reducing the atmospheric $CO_2$ level and can accumulate the SOC simultaneously. The plant biomass also functions as soil covers, which maintain to lower soil temperature in dryland soils. The strategies for the growing of plants in dryland regions are necessary for mitigating climate change by reducing soil temperature.

### 13.2.3 Soil Erosion on Carbon Sequestration

The dryland environment experiences severe soil erosion due to the insufficiency of soil covers, which facilitates the heavy intensity of rainstorms to erode (the Mediterranean basin is an example) (Plaza-Bonilla et al. 2015), and dust storms in the desert areas (e.g., the Sahara Desert). The dryland soils have weak stability structures caused by less content of SOC and the human population pressure. It is reported that 25–55% of soil erosion during the twenty-first century is because of climate change (Delgado et al. 2013). The steep sloping areas of dry lands also aggravate the vulnerability to soil erosion. The detachment of surface soils leads to exposure and is carried away along with the soil carbonates and SOC, increasing the loss of soil C (Lal 2004; Yang et al. 2012). Soil erosion in the dryland regions liberates.

0.21–0.26 Pg carbon/year with 0.02–0.03 Pg carbon/year due to the exposure of organic matter containing carbonaceous material to the climatic factors induced by surface soil erosion. A total of 0.23–0.29 Pg carbon/year was emitted due to land degradation induced by soil erosion (Lal et al. 1999). The release of the SOC is a consequence of disturbing land-utilization patterns, soil degradation processes, and climate change. In dryland regions, the precipitation is uneven and erratic, and it may be very heavy or very scanty, leading to water and wind erosion, respectively, thereby carrying away the SOC from the soil. The role of SOC in dryland soils is important for soil processes—physical, chemical, and biological (Stewart 2016)—and facilitates for growth of plants which can anchor the soils from detachment and has been recognized that the introduction of vegetative soil covers illustrates a significant role in controlling soil erosion with the addition of SOC in dryland soils. This erosion carries away the plant's nutrient content in them, which limits the plant's growth. The practices which reduce the dryland soil erosion in sloppy, as well as flat areas with the enhancement of SOC content, would be the solution for atmospheric carbon sequestration.

### 13.2.4 Soil Organic Matter Content on Carbon Sequestration

The stock unprocessed material as soil organic matter (SOM) is the plant and soil organism's residues, decomposed organic matter, and stable organic matter component of soil. It is mainly composed of C nutrient. The plant residues and their parts consist of higher organic C than the other nutrients. The system that facilitates crop production along with the storing of C in soils is achieving prior environmental attention. The long-term storing of the atmospheric $CO_2$ termed "carbon sequestration" is possible through the plant's SOM. The perennial roots, stable SOM, lumber, and trees are considered long-term stored C (Johnson et al. 2007). In agriculture, the storage of atmospheric $CO_2$ as the SOM from plant biomass is an important long-term carbon sequestration pathway, with protection from microbial degradation as SOM undergoes mineralization and decomposition, to a stable SOM, i.e., humus lasts for hundredfold to thousandfold years mainly made up of C (Stevenson 1994). Dryland soils have less SOM content that can function as SOC stocks. The most effective system is the conservation system by reducing the utilization of fossil fuels, which release the GHGs into the atmosphere (Archer et al. 2002) through the addition of SOM for SOC stocks, and enhancing soil health for growing plants. However, the addition of SOM facilitates the release of $CO_2$ through microbial mineralization processes contributing to climate change. This paves the way to focus on the effect of SOM on soil processes and properties, soil management practices, soil carbon sequestering potential, and short- and long-term strategies (Navarro-Pedreno et al. 2021). The introduction of adequate practices that favor long-term stocks of soil C with the reduction of soil microbial degradation into stabilized SOM is necessary for mitigating climate change in dryland soils.

### 13.2.5 Soil Biodiversity and Livestock on Carbon Sequestration

Soil-living organisms such as bacteria, fungi, protozoa, earthworms, termites, archaea, etc. are the soil's biodiversity. It is approximated that one billion soil bacteria with diverse taxa, 200-meter fungal hyphae, and varieties of micro-arthropods and macro-arthropods are contained in one gram of soil (Roesch et al. 2007; Bardgett 2005), which are interlinked with the surface-ground plant biodiversity providing nutrient cycles, soil processes, decomposition, and mineralization of organic matter processes. These processes facilitate the availability of plant nutrients and maintain soil health, which improves crop productivity. Besides, the livestock grazing in the grasslands of dryland regions supplies an ample amount of organic matter through their residues such as dung or dead matter, which undergo decomposition for SOC stocks in the dryland regions. However, due to constraints in the regions, the existence of organisms and livestock is scarce, thereby less carbon sequestration. The growing of plants supplies sufficient food for soil organisms, which act to decompose the livestock residue matter for SOC stocks and increase the carbon sequestration in the dryland region.

### 13.2.6 Social and Economic Barriers to Carbon Sequestration

The dryland regions are eager for precipitation, SOM content, optimum temperature, and the participation of people with adequate expenditure for sequestering atmospheric $CO_2$. These regions are accompanied by developing countries so as less priority in carbon sequestration as poor people is dominant and less favored for the dryland degraded areas to restore to mitigate the changing climate. The investment in C sequestration not only benefits to the mitigation of climate change but also enhances people's livelihood. The growing of crops, trees, shrubs, herbs, grasses, etc. can acquire the desire for carbon sequestration but chosen of resistant plant species in particular areas, providing continuous irrigation, the introduction of SOM as FYM, vermicompost, green manure, microbial consortia, etc., create complications to the success of carbon sequestration, and developing a stabilized vegetation is a lengthy process which is limited in the under developing countries.

## 13.3 Dry Land as an Organic Carbon Storage Zone

The total C stocks of the dryland region are comparatively lower than the forested regions as expressed in terms of C per unit area due to the soil limitations in temperature, moisture, and coarse-textured structure (Hanan et al. 2021). It is less than 1% as per the soil mass, whereas the cultivated soil under temperate soils has

**Table 13.1** The estimates of organic carbon content (Pg C) of the surface and sub-surface-ground biomass and the SOM under different dryland zones

| Dryland zones | Carbon in surface-ground biomass (Pg) | Carbon in sub- surface ground biomass (Pg) | Carbon content in SOM (Pg) | Total C stocks (Pg C) |
|---|---|---|---|---|
| Humid | 2773.5 | 1006.7 | 512.7 | 4292.8 |
| Dry subhumid | 393.0 | 222.7 | 133.3 | 748.9 |
| Arid | 55.2 | 88.7 | 67.3 | 211.2 |
| Semiarid | 334.7 | 285.6 | 175.9 | 796.1 |
| Hyper-arid | 7.2 | 16.8 | 31.3 | 55.3 |
| All dry lands | 790.0 | 613.8 | 407.7 | 1811.9 |
| Global | 3563.5 | 1620.5 | 920.4 | 6104.3 |
| Total % | 22.1 | 37.9 | 44.3 | 29.7 |

Source: Hanan et al. 2021

1–2%, and the forest and grassland have 4–5%. Therefore, the soil C stock of the top 30 cm depth for surface and sub-surface ground biomass accounts for below 100 Mg/ha in dry.

subhumid (wetter) regions and below 50 Mg/ha in tropical (hot) dryland areas. However, the content of soil C-stocks can be more in high cold latitude dry lands and mesic grasslands (Bardgett et al. 2021). The total C stock in dryland regions accounts for 200 Mg/ha where the sub-surface and surface-ground biomass contribute to 614 Pg C and 790 Pg C, respectively, and SOM carbon (SOMc) content of the surface soil of 0–30 cm depth contributes to 407 Pg C (44% of global SOMc content). The SOMc for 0–200 cm depth soil accounts for 646 Pg C, i.e., 32% of the world's shallow and deep soil C (Plaza et al. 2018). According to Safriel et al. (2005), the upper surface soil of 1 m depth is occupied by a total of 431 Pg organic C, i.e., 33% of the global SOC stocks. Besides, dryland zones of arid and hyper-arid are occupied by 113 Pg, and dry subhumid and semi-arid zones are occupied by 318 Pg of organic C stocks. Many soil scientists have reported different estimates on the global C content in dryland soils. A total C of 1700 Gt (billion metric tons) and 2400 Gt contribute to the soil of 1 m and 2 m depth, respectively, the terrestrial biota (plants and animals) contribute 560 Gt, and the atmosphere has a total C content of 750 Gt. The interesting fact is that the C content in the atmosphere is much lower than the soil content of C, i.e., four times the terrestrial biota content of C and three times that from the atmosphere. A brief estimate of the organic C content under the different dryland zones is presented in Table 13.1. In the Indian context, the present soil organic C stock in the 0–150 cm depth is approximated as 63 Pg, which was 24.3 Pg in the first estimate (Bhattacharyya et al. 2000), presented in Table 13.2. However, the inorganic C content of 1558 Pg C, i.e., 79% of global soil inorganic C, is much higher than the organic C content. The less stock of organic C may be due to

**Table 13.2** The stock of SOC under Indian physiographic regions, estimated from 1800 soil samples

| | SOC stocks (Pg) | Area (m ha) | |
|---|---|---|---|
| Physiographic regions | 0–30 cm depth | 0–150 cm depth | |
| Northern mountains | 7.89 | 18.31 | 55.3 |
| The Great Plains | 3.281 | 10.53 | 72.4 |
| Peninsular India | 3.64 | 13.34 | 54.7 |
| Peninsular plateau | 3.62 | 10.11 | 105.7 |
| Coastal plains and islands | 2.24 | 10.90 | 40.9 |
| Total SOC stocks | 20.99 | 63.19 | |

Source: Bhattacharyya et al. 2000

the tree biomass being at or near zero in dry lands. The increment of the organic C stock in the dryland regions is significantly dependent on the changing climate and land-use patterns that alter rainfall and temperature and then the vegetation dynamics for increasing the accumulation of soil organic C. Regarding the climate change mitigation, the conservation of the present organic C stocks and restoration of the degraded areas will take part an important role in the universal goals for a C-neutral future. Moreover, the soil environment behaves as a medium for the global C cycle between the living and non-living components of the pedosphere, hydrosphere, and atmosphere. So, the soil is responsible for a globally changing climate, and it can also be an ultimate solution. However, the organic C pool is lost from the biotic components at 10–15 Pg and ecosystem carbon of 9–14 Pg, and 13–24 Pg C is lost from the grassland and dry lands due to desertification (Lal et al. 1999; Ojima et al. 1993). The SOC stocks in soil are the only parameter that can improve soil health for better crop productivity by sequestering atmospheric $CO_2$.

## 13.4 Desertification and Organic Carbon Sequestration Potential

Desertification is described as the damaging of the land’s capacity biologically into a desert-like condition (UNEP 1997) operated by the socioeconomic and political elements of the biological and physical functions such as erosion as well as salinization of soil (Mainguet and Da Silva 1998). Soil erosion is predominant in the dryland regions by water and wind agents, especially in the Mediterranean regions, and salinization is mainly in the dryland irrigated areas. In India, soil desertification due to salinization is a major issue. The term “degradation” implies the reduction of the land’s potential due to degradative processes by water and wind erosions and the accumulation of soil sediments. It is not confined to a particular region. It may cause dryland tropics of the USA, humid ecoregions of the high latitude of Iceland, and humid regions of tropical rainforest (Sharma et al. 2012). Alternately, it is defined as dryland destruction in dry subhumid, arid, and semiarid areas due to climatic variation and anthropogenic (human-made) activities (Warren 1996) but is also observed in the Iceland area where a cool and humid climate prevails (Arnalds 2000). The desertification in the humid region is due to misuse of land and faulty soil management practices. It has been affecting and expanding for centuries to many dryland regions due to the ever-increasing population, changing climate, limited food availability, and penury (von Braun et al. 2012; Fleskens and Stringer 2014; Vieira et al. 2015). According to UNEP 1991, the deserted area was estimated to be 3.5–4.0 Bha (billion hectares), i.e., 57% to 65% of the total dryland areas. Out of this, an area of 1.02–1.14 Bha was estimated as degraded soil (Oldeman and Van Lynden 1998). The extent of desertification area is highly varied. It was reported to be 3.6 Bha by 1992, 3.5 Bha by 1984, and 4.0 Bha by 1977 (UNEP 1992). Further, a deserted area estimation of 3.25 Bha and 2.0 Bha was reported by Dregne (1983). Due to human activities, the desertification estimation is increasing at an annual rate of 5.8 Mha, covering 55% and 45% in rangeland and rainfed cropland, respectively, (Mainguet 2012) and 0.13% in the mid-latitudes of the dry lands. The lower potentiality of the deserted soil for plant productivity and prevailing soil degradation leads to a reduction of the soil C pools and less in SOC content. It was reported that a total of 9–14 Pg of SOC pool was lost due to desertification including 10–15 Pg from the biotic or vegetative pools. Various research was conducted in different locations and estimated that 13–24 Pg C was lost from the world's grassland and dryland areas due to soil desertification. The desertification with the reduction of soil C content is speculative to many 20–30 Pg. The sequestration of only 2/3 of the lost C through proper land utilization patterns and management practices of soil can recover 12–20 Pg over 50 years. However, less research is conducted to combat desertification to evaluate the cost and its benefits (Nkonya et al. 2011).

The techniques that combat desertification and result in carbon sequestration in dry lands are perhaps mechanical measures reducing soil erosion by enhancing SOC content contributing to better crop production. It includes SOM management through the incorporation of organic inputs (crop residue, manure, compost) and biological practices including avoiding grazing, fallowing, etc. For instance, a technique called "Zai" enhances both the SOM content and water management, thereby increasing the SOC content levels in a small-scale experiment. Other prominent techniques include the application and burying of biochar, racial chipped wood (RCW), etc.

### 13.4.1 Biochar as Organic Carbon Source

Biochar, simply like traditional charcoal or black C, is a pyrolysis or incomplete combustion product containing highly stable C derived from the feedstocks of plant residue and animal manure and is regarded as an innovative solution for storing organic C in soil with a sustainable approach to the environment and fulfilling the population demands with crop productivity. It is assumed that most of the world's surface soil content is 80% of SOC and 32% sub-surface SOC. The utilization of

**Table 13.3** Biochar effect on soil organic carbon (SOC) in agro-ecosystem and potential mechanism

| Pathway | Observed effect | Potential mechanism | Reference |
|---|---|---|---|
| Direct | More stable SOC fractions;<br>SOC distribution in lower depths | Increase in aromatic ring structure, micro-aggregate stability, aggregation with metal oxides, reduced erosion loss and leaching, sub-soil stabilization, Increased translocation to sub-soil | Lorenz and Lal 2005; Brewer et al. 2009; Rumpel and Kogel-Knabner 2011; Solomon et al. 2012; |
| Indirect | Enhanced crop yield, biomass yield, annual plant species productivity | Increase in water holding capacity (WHC), aggregation, liming effect, CEC, nutrient content (P and K), and resistance<br>To toxic biochar compounds | Verheijen et al. 2009; Sohi et al. 2010; Biederman and Harpole 2013; Glaser et al. 2002; |

**Source:** Lorenz and Lal 2014

biochar dates to ancient times, and recently, it has been used as a strategy for mitigating excess atmospheric $CO_2$ levels by carbon sequestration process and enhancing soil health (Lorenz and Lal 2014). The yield of biochar, physicochemical properties, and C content are highly dependent on the sources and the pyrolysis process (Gupta et al. 2020). The process involves the plants sequestering atmospheric $CO_2$, storing it as plant biomass, converting it into biochar through the pyrolysis process, and incorporating it into the soil that remained for 100 years to millennia as unavailable to living organisms, offering a tool for carbon sequestration but also paving a way for agricultural residue management. The incorporation of biochar in the agricultural field reduces not just atmospheric $CO_2$ but also the emission of methane (CH4) and nitrous oxide (N2O) due to the soil's priming effect. It helps combat desertification as the biochar as a C nutrient will become a food source for soil microbes. However, biochar induced a maximum C/N ratio in the soil, making nutrient imbalance for the soil microbes and imbalance in soil health. The biochar incorporation along with inorganic fertilizers and organic inputs is recommended, however, takes a minimum of 3 years for a stabilized biochar field. The importance of biochar utilization is for mitigating climate change by storing SOC for a long time in soil and restoring degraded dryland areas. However, the application of biochar is still confined to laboratory studies and in small-scale experimental plots, and its adoption in the farmer's agricultural fields is not yet practiced (Gupta et al. 2020). Moreover, the meta-analyses effects of biochar on SOC stocks are still yet to be reported. The long-term observed effects of biochar in the SOC content under agroecological regions and potential mechanisms are given in Table 13.3.

### 13.4.2 Ramial Chipped Wood (RCW) on Carbon Sequestration

Ramial chipped wood is a fresh younger tree and hedge branches, twigs, and leaves rich in C along with nutrients that are buried into the soil as small chips of less than 7 cm diameter for increasing the SOM content in the soil. The structural element of woodchip is C nutrient which accounts for 45–50% (Chandrasekaran et al. 2012). The atmospheric $CO_2$ fixed by the plants through photosynthesis is stored in different portions, and the content of C varies with the species and other photosynthetic factors. The C-stored parts of plants when incorporated in soil function to reduce atmospheric $CO_2$. It has effects on short-, medium-, and long-term benefits to soil properties that contribute to biodiversity by supplying energy sources of low degradation (Lemieux et al. 2000). The application of RCW into the soil lasts long without decomposition as dryland regions have less population of fungi and other microbes. However, the prime target is to increase SOC content; thereby, desertification of dry land can be combated by sequestering atmospheric $CO_2$ into the soil. Due to a lack of studies, the implication is less, even with the wide scope for carbon sequestration in dryland regions affected by desertification.

## 13.5 Soil Organic Carbon Sequestration in Mitigating Climate Change

Climate change is induced by anthropogenic activities that release GHGs that seal the incoming solar radiation in the troposphere and cause greenhouse effects (GHEs), leading to global warming, i.e., rising temperatures than optimal. Ultimately, the climate is changed, affecting the environment and its related factors. This can be mitigated by reducing the GHGs in the atmosphere. The strategy to reduce the atmospheric $CO_2$ in dryland soil is to make sure first of good soil health for net plant productivity. Due to dryland soil's constraints, maintaining soil health is tough, unless the application of farmyard manure (FYM), compost and vermicompost, green manure, microbial consortia, regular irrigation, etc. The foremost step is to maintain a soil condition just for the plant to grow. They require atmospheric $CO_2$, water, and sunlight for photosynthesis. The more the population of plants, the maximum atmospheric $CO_2$ can be sequestered, and climate change can be mitigated. Not only is climate change mitigated but also plant residues are supplied on the surface and sub-surface ground as SOM. In the presence of indigenous soil microbes or from the microbial consortia, mineralization and decomposition of the SOM can accumulate SOC in the form of humic substances, i.e., fulvic acid, humic acid, and humin, in which 143 ± 110–1740 ± 60– 2200 ± 40 and 293 ± 2173 ± 70 years, respectively, are the mean resistance time (MRT) (Wang and Chang 2001). Among them, humin is the most resistant and acts as the main SOC stock. The soil humic substances from the decomposition of fresh SOM become a target at present for mitigating climate change. The vast cultivation and forestation help in storing the atmospheric $CO_2$ into the soil as C stocks for climate change mitigation in the form of humus as it has thousands of MRT.

### 13.5.1 Humus on Carbon Sequestration

Humus is the SOM formed after undergoing biological degradation processes to form a new organic compound that resists further degradation and is completely transformed from its origins (Waksman 1925). Alternately, the different forms of SOM are collectively known as humus (Schlesinger and Bernhardt 2013). The trapped atmospheric $CO_2$ by plants is converted into carbohydrates and stored as organic matter. This helps in holding the $CO_2$ inside the plants and reducing the atmospheric content. It shows that the growth of plants and forestry can increase global warming mitigation. The plant litters trapped atmospheric $CO_2$ and dry matter when incorporated into the soil, due to microbial action converting into humus. The humus contains 60% of C and has more MRT, especially humin. Due to higher MRT, i.e., hundreds to thousands of years, the $CO_2$ as humus is stored and sequestered in the soil, helping in the reduction of $CO_2$ from the atmosphere. The soil C is predominantly found in the humus, but other nutrients (nitrogen, phosphorus, sulfur, potassium, and calcium) are also contained (Dynarski et al. 2020). It facilitates as a substrate for soil microbes and a long-term SOC stock in which SOMc was detected in deep soil aged for several millennia (Krull and Skjemstad 2003). The non-labile form of humus which cannot be metabolized and decayed by the soil microbes persists for thousands of years due to the complex structure with aromatic are the SOC stock. Moreover, the SOM also contains another organic molecule, i.e., lignin as recalcitrant, and persists to decompose owing to its complex formation (Marschner et al. 2008). The study conducted on long-term agricultural experiments showed that the turnover period of free particulate organic matter (POM) is around 50 years (John et al. 2005). The recalcitrant containing lignin prevents it to decompose for decades of years, which directs into organic C stock in the soil.

### 13.5.2 Is there any Specific Carbon Concentration in Soil?

Every substance has a threshold value. As an example, every plant nutrient has its optimum concentration to present in soil and in plants, beyond the optimum level plant shows deficiency or toxicity symptoms. As C is a basic plant nutrient, it also must have an optimum concentration for soil health and plant growth and development. However, regarding this point, there is still a lack of knowledge. To be a healthy soil, only 2% of SOM content is necessary. However, continuous and fast soil mineralization of organic matter always makes insufficiency of C level in the soil, achieving the optimum level of soil C level is tough to reach, and the C-toxic level is more a difficult task in a normal condition. However, the exact optimal concentration of C is not yet known, and the life span of C in the soil is always referred to by turnover time. It is defined as the balance of the total C stored per unit of soil to the flux of output to the atmosphere (Sierra et al. 2017). The output of C may be due to the respiration or leaching process of the organic materials that remained in the soil. The turnover time for the soil C pools is active pools (less than 1 year), slow pools (20–50 years), and passive pools (more than 1000 years) (Parton 1996). The passive pool of C is considered the soil C stock.

### 13.5.3 Improving Soil Health and Mitigating Climate Change

In the two decades ahead, the sequestration of C in the soil as humus is the most cost-effective and long-running strategy for removing atmospheric $CO_2$ causing global warming through plants and accumulating SOM in the soil as soil organic C pools. The amount of SOC stock and SOM types influences soil properties including soil moisture availability, soil aggregate stability, soil compaction, soil erodibility, nutrient cycling, soil exchange capacity, soil buffering capacity, etc. (Krull et al. 2004; Six and Paustian 2014; Murphy 2015; Minasny and McBratney 2018). The SOC stock is an important global C cycle, and its transformation governs the mitigation of climate change. For better soil properties, not only the SOC is important, but balanced nutrient content is also counted. Most importantly, the soil must maintain the carbon and nitrogen ratio (C/N). There is a possibility of disturbing the C/N ratio in the soil during carbon sequestration. Because of this reason, the content of N in the soil gets reduced with the increment of carbon sequestration, so supplying nitrogen sources is also necessary for soil. The nitrogen sources may be organic fertilizers, green manure, inorganic fertilizers, intercropping with legumes, etc. Approaching to sustainable agriculture, and maintaining the environment for eco-friendly, organic N sources should be utilized. But due to high productivity demands, inorganic nitrogen fertilizers are incorporated. The application of nutrients other than the C inputs triggered to mineralization of the stock SOC liberating $CO_2$ to the atmosphere, which is against carbon sequestration, but productivity is also a matter which requires mineralization. The presence of SOC in the soil also improves the soil's biological properties with the enhancement of microbial population, increase in diversity, proper enzymatic functions, and cycle, mineralization, and decomposition processes providing ways for growing plants. They, in return, support the soil microbes with the residues supplied as their food source. A good soil health counts all the physicochemical and biological properties to function well together. However, the concept of soil health maintenance differs with location. The temperate and humid regions experience good soil health as compared with dryland regions. With continuous efforts, the introduction of organic inputs and other necessities to support living organisms (plants and soil microbes) for SOC stock is an advantageous step for improving soil health along with carbon sequestration for mitigating climate change. Besides, unsustainable agricultural management increases the rate of soil degradation, thereby increasing the emission of GHGs and disturbing the C and nutrient cycles (Mehra et al. 2018).

## 13.6 Climate Change's Possible Effects on Soil Quality and Soil Organic Matter

Climate change is a constantly occurring phenomenon that causes changes in soil qualities. It's a global phenomenon that's impacting the region's food security (Brinkman and Brammer 1990; Lal et al. 1994). Due to this reason, it is very much essential to estimate the processes in soil and its condition affecting crop growth. Climate change primarily results in alteration in soil temperature, modifications in rainfall patterns, increase in $CO_2$ levels, and changes in soil moisture contents. And these consequences are becoming political as well as scientific concerns over a decade. Over the past few years, soils appear to be an important resource for supporting the human population as well as food security issues. Most Asian countries are more vulnerable to this challenging issue due to the subtropical climate and huge numbers of small and marginal farmers. Climate change is forecasted to have major consequences on agriculture through direct and indirect impacts. Temperature, precipitation, water holding capacity, soil nutrient availability, and soil structure are all affected directly, while crop yields are affected indirectly. These effects, as well as their interconnections, demonstrate why determining the influence of climate change on soil properties and processes is so complex and unsatisfactory. Pedogenic inertia creates varying time lags and reaction rates during the soil formation processes for different soil types. Soil property changes will be quicker and more intense in the younger, less weathered layers of the Northern Hemisphere's glaciated or desert fringe region and slower and less profound on the equatorial region's stable, continental shields. Due to higher rates of organic matter decomposition, peat soil in the polar and boreal zones will diminish and eventually disappear as temperatures rise.

SOM affects physical, chemical, biological, and hydrological soil qualities and thus plays a crucial role in establishing and maintaining soil fertility. The organic matter turnover rate is predicted to rise as precipitation, temperature, and $CO_2$ concentration increase. Soil organisms have a wide range of temperature optima; therefore a modest rise in temperature is unlikely to have a significant impact on them. They are, however, influenced by increased $CO_2$ limit in the atmosphere, as evidenced by a decrease in the rate of respiration by some decomposers (Alvaro-Fuentes et al. 2009). They are also damaged indirectly because of a higher concentration, which results in the more biodegradable litter, finer plant roots, and a change in the moisture of the soil (Rounsevell et al. 1999). During the winter months, when there is less flora to absorb the nutrients, this could result in a setup of inorganic nitrogen in the soil. Increased precipitation may accelerate the migration of nitrate and phosphorus through agricultural land to freshwater sources (Brisson et al. 2005). Summer algal development is aided by an increase in inorganic nutrients, which leads to a rise in zooplankton, cyanobacterium, and detritus concentrations (Arheimer et al. 2005).

Nutrients may travel through the soil layer or on the surface soil when rainfall intensity surpasses the soil's infiltration rate or when the groundwater water reaches the soil surface from the water table. This problem is exacerbated by inadequate runoff, poor humus levels, and a weak aggregation soil structure. Because phosphorous is tightly bonded to clay particles, a greater risk of phosphorous leaching is expected because of surface runoff and clay particle loss. When using sewage sludge or animal dung to fertilize these soils, there is a huge chance of organic contaminants and microorganisms escaping into the aquifers, as it is heavily damaged by cracking and eventually swelling (Rounsevell et al. 1999).

Increased acidity was seen because of surface runoff and surface leaching due to the depletion of basic cations. Because of the predicted rise in precipitation rates, it is expected that there is nearly a 10–70% increase in N leaching from agriculture. The magnitude of the rise is determined by the type of soil, the amount of nutrients applied, the crop type planted, and the $CO_2$ emission (Arheimer et al. 2005). The impact on soils is mostly determined by factors such as tillage operations, hydraulic conductivity, slope, crop choice, protection zones, and soil type (Eckersten et al. 2001).

## 13.7 Potential of World Soil on Carbon Sequestration

Carbon sequestration is a component of the C-cycle that involves the successive building of organic C in soils. It is calculated using C inputs (organic manure or fertilizers), SOC build-up/depletion, and absorption or storage in the crop production system (Lal et al. 2011). The maintenance of organic C is aided by conditions that encourage lower and slower $CO_2$ evaluation. The phrase “carbon cycle” is used by the IPCC to define the flow of C between the ocean, geological deposits, land, atmosphere, and biosphere, or the exchange of carbon between reservoirs. Carbon sequestration can store up to 14 g of C each year, or nearly 40% of the total amount of $CO_2$ added to the atmosphere each year. The projected total potential of carbon sequestration in soils ranges from 0.4–0.6 Gt carbon/year to 0.6–1.2 Gt carbon/year, depending on a variety of parameters, including time (Barnwal and Kotni 2013). These abilities are computed by multiplying the area of land within a particular ecosystem, which can be transformed into a regenerative land use through the percentage of SOC sequestration under enhanced land use and development system, after which multiplied by the number of years, the land would be maintained underneath the improved system or for the length of time the sink capacity of SOC can be fulfilled. For managing degraded ecosystems, alternate land-use systems, desertification, and regular agricultural management, accurate measurement and control of carbon sequestration potential are essential. However, it needs a coordinated and aggressive effort on a global scale.

As a result of the burning of fossil fuels and changes in land use, carbon in the form of carbon dioxide is presently assembling in the atmosphere at a rate of roughly 34 Pg/year, resulting in global warming and ozone depletion. In its second assessment report, the IPCC anticipated that between 40 and 80 Pg of carbon sequestered in farmland soils might be removed in the next 50–100 years (Mall et al. 2006). Human activity has damaged around 17% of the earth’s surface, resulting in the loss of nearly 20–30 Pg of SOC, which is equal to about 10 years of the current rate of C accumulation in the atmosphere (Joshi and Kar 2009). It is necessary to reduce $CO_2$ emissions into the atmosphere while also increasing removal from the atmosphere through various sequestration mechanisms.

Enhancing $CO_2$ intake by terrestrial ecosystems and controlling emissions use two primary mechanisms essential to carbon sequestration: (1) $CO_2$ input through photosynthesis and (2) $CO_2$ assimilation lifetime. The final capability for terrestrial sequestration is uncertain due to a shortage of basic understanding of both the biogeochemical processes accountable for C transports and retention capacity in the molecular environment on regional and global scales. Furthermore, the composition and behavior of sub-surface ground soil properties, which account for two-thirds of the global terrestrial organic C pool, as well as the sophisticated morphological and molecular processes that drive important biological and ecological phenomena, are little understood.

## 13.8 Climate Change Adaptation and Mitigation

Climate change is an interminable change in weather patterns that can last anywhere from a few decades to millions of years. It describes a long-term statistically substantial alteration in either the climate's base period or its vulnerability. Internal natural phenomena or external factors such as prolonged shifts in the environment or land-use changes could be to blame. It has become a major concern for all countries, causing severe effects on environmental components such as temperature rise, which is mostly due to increased levels of greenhouse gases, which has led to ecosystem deterioration.

Adaptation and mitigation are commonly confused, with the former intending to adjust to the expected rise in temperature and its implications, while the latter aims to reduce GHG emissions. Development of new land-use systems, resource-use efficiency, multiple stress tolerance genotypes, advancement of new agronomic management strategies for climate change scenarios, exploring opportunities for soil maintenance/restoration/enhancement, popularization of resource conservation technologies, and development of spatially differentiated operational contingency plazas are all examples of adaptation strategies, particularly in agriculture and forestry. Human activities created an estimated 169 Gt of $CO_2$, with around 43% of it collecting in the atmosphere (Bhuvaneswari et al. 2014). We need to figure out what adaptation measures could be necessary for agriculture's long-term viability. These changes can benefit individual farmers, society, farms, communities, watersheds, and national levels. Below are a few of the potential adaptation choices.

### 13.8.1 Alternate Land-Use Systems

Land use and land-use change affect directly the duration of crop, soil moisture availability, and local and regional precipitation amount. At the agricultural level, including trees in farming methods leads to higher prosperity. To meet the need for food and fodder while also conserving natural resources, a diversified land-use system should be implemented in the country's many agroecological regions as an alternative to the traditional cropping system. Besides, this method improves the soil's ecological, physical, and chemical qualities. Soil moisture availability, crop duration, and local and regional precipitation amounts are all affected by this land-use change. Including trees in farming systems leads to increased prosperity among farmers at the agricultural level. A diversified land-use system should be adopted throughout the country's multiple agroecological areas as an alternative to the traditional cropping system to match the requirement for food and fodder while also conserving natural resources. This process increases the physical, chemical, and ecological properties of the soil. They help boost crop yields and ensure future production stability by fixing nitrogen from the air; solubilizing phosphorus, potassium, and zinc by increasing the quantity of solubilizing and mobilizing bacteria; and recycling nutrients from the soil all while helping to increase crop yields and achieving better long-term biological and economic productivity. In addition to conserving rainwater where it is needed, alternative land use in farms helps reduce soil erosion and preserve vital topsoil, reduce the severity of downstream flooding, and protect watershed construction materials. In semiarid places, they operate as a living barrier, protecting vegetable and grain crops from livestock that would otherwise destroy them.

### 13.8.2 Agroforestry

The land-use systems and practices for both woody perennials such as shrubs, hedges, trees, etc. and crops along with livestock on a unit piece of land are considered "agroforestry." Within the system, the requirements of the growing plants and livestock are maintained sustainably, and the sequestration of atmospheric $CO_2$ is through woody and agricultural plants. Besides, the livestock supply the residues and their dead matter, which undergo decomposition and support the plants. It can be considered a close system working for carbon sequestration. The forest, grazers, and crops of agroforestry became an important component for mitigating climate change. Trees were realized as an important means for capturing atmospheric $CO_2$ in terms of soil, vegetation, and biomass product (Malhi et al. 2008). According to the Kyoto Protocol, agroforestry is approved as the higher mitigating the GHGs zone, especially the afforestation and reforestation systems. Thus, it is attracted as a carbon sequestration zone (Nair and Nair 2003; Haile et al. 2008) and provides attention to adoption in the desertification areas of dryland regions The estimation of the capacity of agroforestry on carbon sequestration is contributed by the information of above-ground biomass, the C content in soils, and average C stocks per unit time (Nair et al. 2009). The agroforestry system for over 50 years can enhance the SOC content up to 2.2 Pg in the above- and below-ground biomass. For developing a country, the less extent of agroforestation and the area coverage under tree woodlots, multi strata system, tree intercropping, protective system, and silvopasture accounts for 50 Mha, 100 Mha, 700 Mha, 300 Mha, and 450 Mha respectively. The capacity of agroforestry to store SOC is up to 300 Mg C ha-1. However, there is still a lack of knowledge on how fast atmospheric $CO_2$ can be sequestered and how much $CO_2$ is released into the atmosphere, suitable plants, and livestock/grazer species as per the regions, rate of sequestration, and contribution of SOC in soil needs further research, long term storage of SOC is finite or not is understood depending on the availability of the soil binding sites, i.e., soil mineral contents and its depth. With the enhancement of this lacked knowledge, proper agroforestry can be developed with mitigating climate change through carbon sequestration in the dryland region. Moreover, desertification can be managed even though adoption and stabilization of the management practices are quite a tough and long-term process in dryland areas.

The management of an integrated tree-crop and livestock system in a specific region enhances productivity while guaranteeing long-term viability. It aids in the recycling of nutrients by lowering pressure on land-based forests and deep-rooted trees. Increased organic matter lowers nutrient leaching, surface runoff, and soil erosion by increasing soil coverage. Many trees may thrive in saline water with an EC of less than 10 dS/m. Among the potential trees are neem tree (*Azadirachta indica*), ber (*Ziziphuss mauritiana*), mesquite (*Prosopis juliflora*), wood apple (*Feronia limonia*), kassod tree (*Cassia siamea*), gum arabic tree (*Acacia nilotica*), forest red gum (*Eucalyptus tereticornis*) *Tamarix* spp., *Salvadora* spp., etc. (Fleming 2010). Of the forage grasses studied, *Panicum laevifolium* produced the largest forage biomass, followed by *Panicum maximum*. Fruit trees such as karonda (*Carissa carandas*), Indian gooseberry (*Emblica officinalis*), ber (*Ziziphus mauritiana*), and bael (*Aegle marmelos*) were found to be promising. In the inter-spaces, crops such as cluster bean, pearl millet, sesamum (during *Kharif*) and barley, and mustard (during *Rabi*) proved to be highly beneficial. Non-traditional crops that could be grown include castor (*Ricinus communis*), aloe vera, dill (*Anethum graveolens*), taramira (*Eruca sativa*), Isabgol (*Plantago ovata*), and lemongrass (*Cymbopogon flexuosus*).

The addition of trees to grasslands in slick terrain gives stability and protection from harsh events like floods and storms. Enhanced soil porosity from tree roots and shade offered by leaf cover minimize runoff, which can help improve drought resilience. Tree shade reduces evapotranspiration in some crops, such as coffee, and helps alleviate microclimate extremes, which are expected to become more common as the climate changes.

### 13.8.3 Efficient Water Management Techniques

Climate change may influence presently irrigated areas and exceed current irrigation capacity due to overall water challenges, but farmers without accessibility to irrigation should be the most susceptible to the changing environment. As a result, ideas, technologies, and expenditures that improve water use efficiency or irrigation availability or finding methods to promote revenues with less dependable and more unpredictable water sources is critical. Micro-irrigation is gaining popularity to get the most out of every drop of water. Improving system delivery inefficiencies also demands investment and farmer participation in integrated water management. In overexploited regions like Punjab, Haryana, and Tamil Nadu, rational pricing of surface and groundwater is needed to discourage injudicious and excessive use of water for production, whereas infrastructure investment could create conditions where groundwater is better utilized in areas where groundwater is less used, such as eastern India.

### 13.8.4 Resource Conservation Technologies

Resource conservation technologies (RCTs) that increase soil quality, irrigation, crop production, and farm income include zero-tillage or conservation tillage, legume-based crop rotation, mulch/ground cover farming, sowing timing alterations, selection of robust crop varieties, and bed planting (Gupta and Seth 2007). These adaptation tactics combine old and modern technology to eliminate unnecessary off-farm inorganic inputs, boost agriproduct diversification while optimizing production output to the landscape's ability, and restrict off-farm inorganic inputs. Zero-tillage is used by farmers in Northwestern India, mostly in regions where rice is harvested late. In wheat cultivation, ZT has been proven to save 13–33% water and 75% fuel; however, bed cultivation could also save 30–50% water (Malik et al. 2002). Furthermore, resource-conserving methods reduce $CO_2$ concentration in the atmosphere by limiting the release of soil C (Kukal et al. 2005). By incorporating organic matter into soils, conservation agriculture enhances the soil moisture ability and hence improves water consumption potential. The strategy also minimizes carbon emissions by reducing tilling activities because the system is not restored at each planting. However, it demands more comprehensive pest and disease management.

In addition, new technology such as minimum tillage, micro-irrigation, and poly-housing technology to grow crops in difficult climates has been created to resist the consequences of climate change. Water management, as well as area-specific fertilizer management, genetically manipulated (GM) crops, solar and wind energy, laser land leveling, upgrading with some of the most up-to-date agro-metrological data, use of heat and drought-resistant crops, raised bed planting system, adoption of a groundwater recharge technique, seed treatment, and adoption of a crop simulation model, could also help mitigate the effects of climate change. Line spacing, crop diversification, altering sowing time, crop intensity, and farm operation are all agronomic practices that can help manage climatic risk. RCTs may result in the reduction of water and energy usage (fossil fuels and power); minimize GHG emissions, soil erosion, and deterioration of the resource base; improve yields and agricultural profits; and reduce labor shortages.

## 13.9 Development of Policies Related to Carbon Sequestration in Dry Land

In the present *scenario*, drastic climatic changes are observed that have caused various phenomena such as melting of glaciers, thawing of Arctic permafrost, shrinkage of polar ice caps, etc. These changes can be considered key climatic indicators on the planet, and to better understand these, the Intergovernmental panels on Climate Change (IPCC) was established in the year 1988. It mainly consisted of three working groups and hundreds of climatologists and specialists. IPCC was mainly established to analyze climate change studies, climatic data, current developments, and regions impacted due to climatic changes. Climate change manifests itself in the form of weather variations, rainfall variations, temperature fluctuations, catastrophic catastrophes, and so on (Srinivas and Sridevi 2005).

The most important aspects associated with carbon sequestration in dryland environments were the ability to serve efficiently to the farming sector, ecological sustainability, and poverty reduction. This should be flexible in determining adaptive management for degraded areas, which can be accomplished through a smart policy approach. And so, this policy approach should be centered on expanding our knowledge of nature as well as its elements. It should be capable of creating a massive chance for farmers to be strengthened by introducing appropriate incentives or subsidies to inspire them to generate more and better. Aside from these laws and regulations for farmers, one must also analyze the farmer's decision- making ability, which is represented in terms of land he possesses, the number of assets he owns, the family size he has, and the farmer's economic state. Carbon is generated as GHG from dryland ecosystems because of land degradation, leading to a rise in poverty in this region. Therefore, while establishing strategies, we must place more emphasis on ecological services and carbon management, as well as poverty alleviation and sustainable development. Policies should be region-specific and tailored to the needs of small and marginal stakeholders, as well as villages. Carbon management techniques in dryland ecosystems for poverty reduction and sustainable development were also included in the United Nations Framework Convention on Climate Change (UNFCCC) and the United Nations Convention to Combat Desertification (UNCCD). As a result, a variety of global policies are being designed to improve dryland carbon storage mechanisms, including the United Nations Global Mechanism Program, which was established in 1994 to address desertification and land degradation issues, and the Global Environment Facility Program, which was established in 1992 to provide monetary assistance from the adaptation fund to address degraded land (Kalra et al. 2007).

## 13.10 Conclusions

Dryland ecosystems constitute around 47.2% of surface area and support over 38% of the total human population. It covers about half of the global area, so it has sufficient land to manage the atmospheric excess $CO_2$ level trapping into it as SOC stocks for thousands to millennia years which is possible with the adequate growing of plants, i.e., vegetation. The application of organic inputs along with irrigation to facilitate vegetation is an emerging practice in the dryland region, which is the source of SOC stock. Inefficient management practices, poor policies framework, and inadequate land-use decisions cause a significant loss of C in dryland areas. Apart from this, global warming will also add a greater threat to agriculture production and social sustainability by escalating water scarcity problem in these areas. However, by adopting proper measures, we can efficiently manage atmospheric $CO_2$ through carbon sequestration measures, which ultimately improve the socioeconomic condition of the regions. Researchers should focus more on agriculture management systems in dryland areas that enhance the carbon footprint of the region. Future research should be more specific to carbon cycling and ecosystem services. Government should frame the policies in such a manner that it should strengthen the socioeconomic conditions of the farmers, which can be done by providing incentives and conducting capacity building programs to improve their knowledge about carbon management strategies.

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# Soil Inorganic Carbon in Dry Lands: An Unsung Player in Climate Change Mitigation

# 14

Kiran Pilli, Bishnuprasad Dash, Biswabara Sahu, Jaison M, and Durgam Sridhar

## Abstract

In dryland soil ecosystem, soil inorganic carbon (SIC) is a hidden treasure, which refers to the parent rock carbonate formed during weathering process of silicate carbon, commonly occurring in the form of calcite or dolomite. Generally, in dryland regions, high evapotranspiration along with moisture deficient situation promotes formation of SIC. Apart from its (SIC) potential as atmospheric $CO_2$ sink, it may play an indirect positive role in soil aggregation through the interaction between carbonates and soil organic matter. During the amelioration of sodic soils in dryland regions, SIC acts as a modifier or ecosystem engineer. Anthropogenic activities including unsustainable land use practices and injudicious use of water are the major driving forces for increasing the coverage of global dry lands. The largest accumulation of carbonates occurs in the soils of arid and semiarid areas because of the conducive environment created under dryland ecosystem due to calcification and formation of secondary carbonates. As a result, SIC plays an important role in soil C sequestration and global C cycle. Soil erosion and arid

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conditions coupled with climate change (drought and heat waves) are posing challenges to dry lands, which strongly influence the carbon cycle due to erosion-induced loss of carbon. Therefore, to unlock the potential of dryland SIC and climate change mitigation, desertification must be controlled to achieve land degradation neutrality.

**KeywordsKeywords**

Soil inorganic carbon · Dry lands · Climate change · Secondary carbonates

## 14.1 Introduction

The emission of carbon dioxide is a core environmental issue in recent decades, especially regarding the United Nations Framework Convention on Climate Change (UNFCCC). In the present scenario, carbon sequestration is considered as a link to mitigate global warming by checking $CO_2$ emission, a major greenhouse gas (GHG) causing climate change from various sources. Political responses were thus focused to create sustainable approaches for different inducers of $CO_2$ like industry, transportation, energy sectors, agriculture, etc.

Soil inorganic carbon (SIC) accumulation occurs by carbon dioxide ($CO_2$) emitted during soil respiration, weathering of parent materials, and accumulation of eolian dust and also due to soil water content and C input from precipitation (Cihacek and Ulmer 2002; Lal 2004). Soil inorganic carbon refers to the parent rock soil carbonate formed during the weathering of silicate carbon having a very high accumulation rate and is easily affected by climate, water, parent material, etc. This is also the dominating form of soil carbon pool observed in arid and semiarid regions. SIC includes three phases of carbon present in the soil system i.e., as gaseous phase ($CO_2$), liquid-phase carbonates ($CO_3{}^{2-}$) and bicarbonates ($HCO_3{}^{-}$), and solid-phase carbonates such as $CaCO_3$, $MgCO_3$, and $Na_2CO_3$. Solid-phase carbonates are the main constituent of soil inorganic carbon, in cases of soil with pH >6.5 and good drainage conditions, whereas inorganic carbon present mainly as gaseous and liquid phase are negligible (Xu et al. 2014).

SIC accumulation is relevant to dry lands because of high evapotranspiration coupled with moisture deficit situation in arid and semiarid regions. The increase in SIC stocks in dryland soils makes them the largest pool of global soil C stock (Eswaran et al. 1993) and plays an important role in soil C sequestration and global C cycle (Lal 2004; Mikhailova and Post 2006). SIC apart from its potential as atmospheric $CO_2$ sink may also play an indirect pivotal role in improvement of soil structure by encouraging the interaction between soil separates, carbonates, and soil organic matter.

## 14.2 Carbon Sequestration in Dry Lands

Dry lands globally cover about 4.9 billion hectares of land and are considered as a potential source of soil inorganic carbon in calcic and petrocalcic horizons (Lal 2004). These soils are characterized by the presence of high concentrations of soluble salts like carbonates and bicarbonates of $Ca^{+2}$, $Mg^{+2}$, $K^{+}$, and $Na^{+}$. Out of the global total SIC pool, around 97%, i.e., 916 Pg of SIC, are estimated to be present in dryland soils (Lal 2004). In arid and semiarid regions, the largest stock of carbon is present as SIC (≈950 Pg of soil carbonate + 1404 Pg of bicarbonate in groundwater) within 0.1 m depth and could be a significant source as well as sink of carbon (Ferdush and Paul 2021). The occurrence of two types of inorganic carbonates in soil is reported: one is "primary" or "lithogenic" carbonates, and second is "secondary" or "pedogenic" carbonates. Lithogenic (primary) inorganic carbonates are inherited from parent rock materials, whereas pedogenic (secondary) inorganic carbonates are formed by re-precipitation of weathered materials and dissolution of primary carbonates. During the secondary carbonation process, calcium and magnesium present in the soil react with two units of atmospheric $CO_2$ in the presence of water and gets leached down to the subsoil resulting in subsequent re-precipitation. Thus, precipitation of pedogenic carbonate can also sequester $CO_2$ on the land surface by consuming one mole of atmospheric $CO_2$ by calcium and other elements (Mg, Fe, Na, Mn, etc.) through silicate weathering (An et al. 2019; Beerling et al. 2020), which was described by the following equations:

$$CaCO_3 + CO_2 \downarrow + H_2O \rightarrow 2HCO_3{}^{-} + Ca^{2+} \tag{14.1}$$

$$2HCO_3{}^{-} + Ca^{2+} \rightarrow CaCO_3 + H_2O + CO_2 \uparrow \tag{14.2}$$

$$2CO_2 \downarrow + 3H_2O + CaSiO3 \rightarrow H_4SiO_4 + 2HCO_3{}^{-} + Ca^{2+} \tag{14.3}$$

$$2HCO_3{}^{-} + Ca^{2+} \rightarrow CaCO_3 + H_2O + CO_2 \uparrow \tag{14.4}$$

Formation of pedogenic carbonates in soil mainly depends on land use and soil or crop management systems. Secondary carbonates like calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$) are formed by dissolution of $CO_2$ (produced from addition of bio-solids and their decomposition) in water leading to formation of carbonic acid. In some dry lands, carbonates are present as a solid layer called "caliche" or "calcic" horizon, which refers to crust of Ca and Mg carbonates. Dry lands may store about 95% of global SIC through the formation of caliche or concrete (Marion et al. 2008). These horizons are formed by accumulation of secondary carbonates ($CaCO_3$ and $MgCO_3$) and by leaching of carbonates from surface soils or by upward movement of carbonates with the capillary water in such regions (Lal 2004). It is also well-known that soil microbial activity, pH, and the rate of organic matter decomposition are influenced by the free forms of carbonates present in soil. Sequestration of SIC occurs via the movement of $HCO_3{}^{-}$ into groundwater following subsequent reaction with Ca and Mg and reprecipitation in

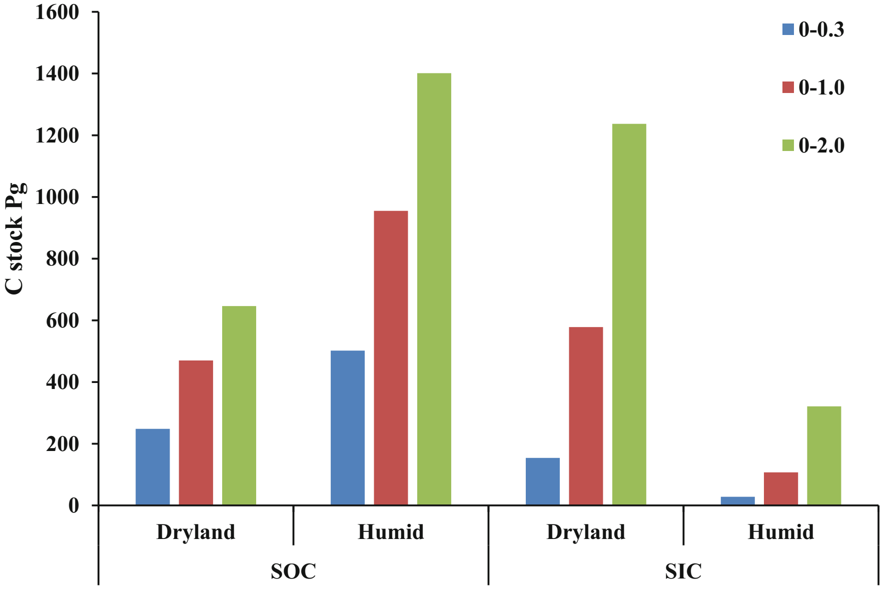

**Fig 14.1.** Global soil C stocks to different depths (cm) and climatic conditions (Adapted from Lal 2019)

closed systems, i.e., in subsoil horizon. The role of SIC sequestration on soil C dynamics in relation to the climate change is less understood than that of SOC sequestration. There is a strong need to assess the formation of secondary carbonates, the magnitude of leaching, and the impact of land use and management of overall SIC dynamics.

In the past years, intensive cultivation has led to a loss of 40 Pg soil carbon globally with an average rate of about 1.6 Pg C year$^{-1}$ (Smith et al. 2008; Verma et al. 2015). High amount of C loss occurs mainly from surface soils prone to erosion, salinization, and nutrient diminution than the undegraded soils with a range varying from 10 to 30 Mg C ha$^{-1}$ (Lal 2013). The historical total C losses from global soil are estimated to be 78 ± 12 Pg (Lal 2004; Buragohain et al. 2017).

Dry lands are increasing globally because of intensive climate change and other anthropogenic activities. The world's total dryland area is increasing drastically and now constitute approximately 45.36% of the earth's land area, or in terms of area, out of 147 M km$^2$ total world surface area, 66.7 M km$^2$ is dry land (Prăvălie 2016). Out of the 45.36% area that comes under dry land, 11% is used as cropland and 30% as pastures (Plaza et al. 2018). These dry lands provide numerous ecosystem functions and services, including sequestration of atmospheric $CO_2$ (Lal 2004). The reservoir of carbon in inorganic form is almost double as compared to the carbon in organic form in such soils, for example, Fig. 14.1 show that SOC stock in top 2 m depth in dry land is estimated at 646±9 Pg, while the SIC stock is 1237±15 Pg as per a study conducted by Plaza et al. (2018).

In India, the southwest monsoon is blocked by very tall Western Ghats to reach Deccan Plateau, so the region receives very little rainfall, which leads to spreading of dryland regions. The dominant soils in these regions contribute about 10% of soil organic carbon (SOC), 18% of soil inorganic carbon (SIC), and 13% of total carbon (TC) (Srinivasarao et al. 2020). This region occupies nearly 45% area of the country and covers the semiarid tropics (SAT) of the Indian subcontinent. The semiarid tropics of India are dominated with black soils (*vertisols* and some *entisols*) along with red soils (*entisols* and *alfisols*). In Indian soils too, there is a dominance of inorganic carbon stored in soil as compared to soil organic carbon. For example, soil organic carbon pool in soil profile is estimated to be 21 Pg and 63 Pg up to 30 cm and 150 cm depth, respectively, whereas soil inorganic carbon (SIC) pool is estimated to be 196 Pg up to 1m depth. The carbon storage capacity of soils depends on the quality of soil substrate and its surface charge density (SCD). The carbon sequestration potential in Indian soils is estimated at 7–10 Tg C $y^{-1}$ for restoration of degraded soils and ecosystems, 5–7 Tg C $y^{-1}$ for erosion control, 6–7 Tg C $y^{-1}$ for adoption of recommended management practices (RMPs) on agricultural soils, and 22–26 Tg C $y^{-1}$ for secondary carbonates. Thus, total potential of soil C sequestration is 39–49 (44 ± 5) Tg C $y^{-1}$ (Lal 2015).

The soils in these southern hills and plateau are dominated by smectites and kaolinite minerals and have greater carbon sequestration potential of 38% of SOC, 43% SIC, and 39% of TC (Srinivasarao et al. 2020). The soils in dryland areas have less scope to sequester soil carbon in organic form due to high rate of decomposition and oxidation (because of high temperature and rainfall) while possessing a great potential to sequester carbon in inorganic form if appropriate management and land use policies are followed (Marks et al. 2009).

## 14.3 Dry Land: A Store House of SIC

- Microbial activity and vegetation play an important role in SIC accumulation in soil. Enhanced microbial activity under cultivation practices receiving conjoint application of organic and inorganic fertilizers increased emissions of carbon dioxide ($CO_2$) through process of soil organic matter decomposition and microbial respiration, which was trapped in soil solution following subsequent precipitation of carbonates ($CO_3^{2-}$ and $HCO_3^-$ ions) that led to increase the SIC accumulation in soil (Cihacek and Ulmer 2002; Mikhailova and Post 2006; Yu et al. 2014).
- During dry season, upward capillary movement of groundwater rich in Ca and Mg reacts with $CO_3^{-2}$ and $HCO_3^-$ to form secondary carbonates ($CaCO_3$ and $MgCO_3$), and freezing during winter season can increase SIC in soil (Carling 1984; Lal 2004).
- Management practices, such as irrigation, manure application, cropping system, and integrated nutrient management, can affect SIC. Integrated nutrient management along with application of organics like FYM and compost provides a better

niece for microbial activity in soil. It enhances SIC sequestration via microbial activities as discussed above.
- Irrigation water acts as a important catalyst for SIC sequestration in dryland ecosystems as it facilitates movement of carbonates and bicarbonates into sub soil layer. Cropping systems of varying rooting depth also play a vital role in carbon accumulation under dryland condition. Deep-rooted crops enhance allocation of carbon in subsoil, thereby improving its sequestration.

## 14.4 Factors Affecting SIC Storage

### 14.4.1 Soil Factors

#### 14.4.1.1 Soil pH

The weathering potential of soil can be accelerated by increase in atmospheric $CO_2$ and biologically derived $CO_2$ by fluctuating the rate of reaction of cation exchange, acidification, and buffering capacity of soil and mineral dissociation (Oh and Richter Jr. 2004). Dissolution of atmospheric $CO_2$ in soil water forms carbonic acid, leading to acidic soil conditions. The soil $CO_2$ and carbonic acid ($H_2CO_3$) causes acidity and weathering of soil minerals. The soil with high clay content often have low pH (Liu et al. 2014), which corresponded to low SIC concentration (Dorak et al. 2017).

#### 14.4.1.2 Soil Microbial Activity and Respiration

Soil inorganic carbon pool is significantly influenced by microbial activity through photosynthetic assimilation of atmospheric $CO_2$ in their biomass and distribution in belowground parts, which adds to the total organic carbon in soil, alarming carbon recrystallization (Zhao et al. 2020). The organic acids which are produced during decomposition will break down to dissolve inorganic carbon, which leads to precipitation of carbonate minerals (Braissant et al. 2002). $CO_2$ produced through biogenic process by plant roots and microbial respiration under belowground occurs mainly as dissolved form (DIC) contributing to pedogenic carbonate formation.

#### 14.4.1.3 Other Soil Physicochemical Properties

The conversion of soil $CO_2$ to carbonates ($CaCO_3$) or bicarbonates ($HCO_3$) varies with various physicochemical properties of soil like type of soil, soil pH, soil moisture, temperature, degree of salinity, and soil depth. High temperature and rainfall during summer in arid and semiarid regions lead to mineralization of soil organic matter and high rate of biological respiration improving partial soil $CO_2$ pressure. Elevated $CO_2$ in soil air combines with soil water to form carbonic acid solution, which can dissolve carbonate (Pan 1999). In dry areas, irrigation water leaches out the soil carbon. The depth of soil water movement is limited, and the transport of inorganic carbon is also restricted, thus leading to profile distribution of inorganic carbon in soil. The inorganic carbon distribution in dryland area with saline alkali varies with the depth of soil layer, i.e., about 80% of inorganic carbon is stored below 1 m depth, and ~ 50% inorganic carbon is stored below 3 m depth

(Wang et al. 2013). In saline soils, salt concentration had a significant negative correlation with inorganic carbon and density of soil profile (Yan et al. 2017). SIC concentration is usually positively correlated with evaporation and mean annual temperature (MAT), but negatively correlated with mean annual precipitation (MAP) (Wu et al. 2009; Han et al. 2018). Soils with high clay content corresponded to low SIC concentration (Dorak et al. 2017). However, researches are still continuing to further unravel the clear-cut effect of all the soil factors on SIC.

### 14.4.2 Anthropogenic Factors

Anthropogenic and non-climatic factors such as excessive use of nitrogenous fertilizers, land management practices, tillage operations, and deforestation may influence the carbon pool by intruding properties like soil pH, precipitation, erosion, and leaching. However, understanding the changes in soil inorganic carbon (SIC) resulting from anthropogenic factors is vital for evaluating terrestrial soil C stocks and predicting global change.

Fertilizer application to degraded and low-fertile soils is one of the essential management strategies for crop production. Application of chemical and manure fertilizers to any soil can alter the SOC and SIC. Long-term fertilizer application of nitrogen (N) and phosphorus (P) along with manure (NPM) influenced the soil total carbon than NP application in all particle size fractions (sand, silt, and clay). Fertilizer application improved SOC content in sand and silt fractions. But SIC responded differently in three particle fractions and fluctuated more in clay and coarse fractions because the carbonates show different stabilities based on particle fractions in soil (Dong et al. 2017). Soil acidity and leaching induced by fertilizer application may cause an unrecoverable change in SOC and entirely loose SIC stock by $CO_2$ emission (Zamanian et al. 2018; Zamanian and Kuzyakov 2019). Acidification of carbonate containing soils lost SIC about 0.3 Pg (Zamanian et al. 2018; Zamanian and Kuzyakov 2019; Zamanian et al. 2021) and 0.8 Pg of SOC in the form of $CO_2$ to atmosphere (Goldstein et al. 2020).

Afforestation increased the SOC across different sites and soil depths. But the SIC increased relatively in drier sites and decreased in wetter sites. Afforestation showed consistent increase in SOC, but variable response of SIC. Soil clay content, precipitation, soil temperature, and aridity index are directly proportional to SOC and inversely proportional to SIC (Jia et al. 2019). Afforestation of Drylands increased the SIC through increase in the decomposing rate of litter input and organic carbon ultimately facilitating the release of CO2 into the soil, which is precipitated as bicarbonates and carbonates by reacting with soil minerals (Lal 2008, Zhang et al. 2013 and Zamanian et al. 2016). The interception and deposition of fine soil particles from the wind-sand flow by the plant canopy after afforestation also contribute to SIC accumulation. Fine soil particles contain large amounts of carbonate, resulting in rapid SIC accumulation (Wang et al. 2006). Restoration of grasslands decreased the SIC (Liu et al. 2014), whereas degradation increased SIC. Revegetation of degraded lands with shrubs was helpful for SIC fixation compared to trees and grasses (Zhao et al. 2016). Therefore, the influence of land management on SIC, particularly in semiarid and arid regions, is still an open question but is critical to quantify SOC and SIC budgets. Land use change from grassland to farmland increased SIC by 30.6%, and grassland restoration from farmland to grassland decreased to 14.4%. Changes in SIC were affected by soil pH and mean annual temperature (MAT). An et al. (2019) reported that SIC increased across all land use change types (grassland to farmland, grassland to forest, farmland to grassland, farmland to forest, sand land to forest), while the magnitude and direction of SIC change varied greatly with different land use change types. The changes occurring in SIC are mainly due to the changes in soil pH, temperature, and concentration of soil $CO_2$, which drive the dissolution and precipitation of carbonates in soil (Wu et al. 2009; Liu et al. 2014; Zhao et al. 2016) but regulated by soil organic matter (SOM) accumulation (Han et al. 2018). The increase in soil organic matter may decrease the SIC by release of hydrogen ions associated with organic anions (Liu et al. 2014) and decomposition of SOM release $CO_2$ (Wu et al. 2009) which accelerate the carbonate dissolution in soil.

## 14.5 SIC and Climate Change

It has been assumed that the arid climate is responsible for the formation of SIC (pedogenic calcium carbonate), and this is contrary progression to the enrichment of SOC. The increase in C sequestration through enhancement of SOC in the soil would induce dissolution of native calcium carbonate, and the leaching of SIC in arid climate would also result in carbon sequestration (Sahrawat 2003). The Indian subcontinent is blessed with diversity of soil and climatic conditions. In the tropical regions, various climatic parameters like temperature and annual precipitation continue to remain as a potential threat for soil inorganic carbon sequestration. Therefore, arid climate will be a curse for Indian agriculture by causing soil degradation in terms of depletion of SOC and formation of pedogenic calcium carbonate with the simultaneous salinity and sodicity development in soil (Eswaran et al. 1993).

Climate change mitigation mainly focused on enhancing C sequestration through SOC and decreasing $CO_2$ emissions. The contributions of SIC in divergence to $CO_2$ emissions are usually neglected due to its stability in soil. However, increase in soil acidification due to intensive agricultural practices, nitrogen fertilization and high atmospheric deposition decreases the SIC stocks, leading to increase in unaccounted $CO_2$ efflux and leaching of bicarbonate at greater soil depths (Zamanian et al. 2018; Raza et al. 2020). Moreover, remediation of acid soils in the form of lime application frequently subjected to addition of Ca and Mg carbonates, which is another direct source emission of $CO_2$ into atmosphere. Consequently, efforts made to mitigate climate change through SOC sequestration need a revisit as SIC-borne C losses are significant both in terms of C stocks and soil fertility loss, upon which future SOC sequestration will be reduced (Raza et al. 2021). Climate change factors like increase in temperature and atmospheric $CO_2$ and increase in drought intensity periods influence the transformations of soil carbon. The rise in temperature increases $H^+$

ion inputs by accelerating nitrification rates, ammonia volatilization, and mineralization of organic matter. Increase in moisture facilitates carbonate dissolution and can cause acidification if base cations are leached. High rainfall intensity also increases carbonate losses with runoff and erosion. Nitrification process in soil is inhibited in flooded conditions were plants utilized more $NH_4^+$ release more $H^+$. Increase in $CO_2$ concentration in the soil with moisture facilitates formation of carbonic acid, which causes acidification. Nitrogen assimilation usually becomes low with increase in $CO_2$ concentration and results in N losses and acidification. Root exudates are increased at higher $CO_2$ concentration, which usually end up in organic acids. Root exudates also increase microbial activity and accelerate organic matter mineralization. All processes and fluxes driving SIC losses are increased with increase in the intensity of climate change factors (Raza et al. 2021).

## 14.6 Conclusion

Anthropogenic activities including unsustainable land use practices and injudicious use of water are the major driving forces for spreading the anchorage of global dry lands. Predominance of pedogenic processes like calcification and formation of secondary carbonates under dryland region creates a conducive environment for accumulation of SIC in soil. Sequestration of the atmospheric $CO_2$ as SIC in arid and semiarid regions to mitigate climate change is a promising option, but its dependency on several physical, chemical, and environmental factors that control spatial and temporal distribution of SIC under elevated $CO_2$ in the atmosphere as well as soil poses challenges in achieving SIC sequestration under changing climatic scenario. Therefore, existing C budget schemes and models should include SIC dynamics to provide an accurate and comprehensive representation of the C cycle specifically for dry lands, which would help formulate relevant policies and control measures.

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# Remediation of Polluted Soils for Managing Toxicity Stress in Crops of Dryland Ecosystems

# 15

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## Abstract

Soil pollution arising from either inorganic or organic sources causes undesirable change in the physical, chemical and biological characteristics of the soil and affects the environment as well as plant and human life through the food chain. Major inorganic contaminants include heavy metals, radionuclides, nanoparticles and asbestos, whereas organic contaminants are carbon-based molecules such as antibiotics, pesticides, radionuclides, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), halogenated organics and volatile organic compounds, by-products from mining and petroleum industries, etc. Many of these foreign substances are highly persistent and accumulate in the soil, thereby posing severe threat to agricultural productivity and soil sustainability. As healthy and fertile soil are pertinent to healthy crop production in drylands, removal of these pollutants through various remediation measures that reduce their toxicity and restore soil to its original functional capacity is gaining considerable attention in recent years. This chapter elucidates the different forms of soil pollutants and their major sources, their adverse effect on crop morphology and physiological processes. It also discusses various in situ and ex situ remediation methods that have been developed over the past few decades. These remediation technologies employ physical, chemical, electrical, thermal and biological methods to clean up polluted sites. Strategies include containment, transformation and/or transport based. Choice of any remediation method depends on the nature, origin and magnitude of contamination; effectiveness, efficiency and cost of the technology; and topography, soil structure and physicochemical properties of the polluted site. A combination of two or more remediation approaches may also be employed to improve the efficiency of remediation. Even though many remediation

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technologies are available at present, owing to the cost and time involved, it is of paramount importance to prevent soil pollution.

**Keywords**

Soil pollution · Contamination · Clean-up · Pollutants · Heavy metals

## 15.1 Introduction

Soil acts as sink of various pollutants. Accumulation of soil pollutants negatively influences soil properties and disturbs the functioning capacity of a soil by altering soil physical, chemical and biological properties, thereby rendering the soil less productive or unsuitable for human use, and such soil are said to be polluted. In general, pollutants may be broadly classified into organic and inorganic pollutants. Inorganic pollutants include heavy metals and metalloids, radionuclides, mineral acids and bases, salts, asbestos, etc. Organic contaminants are carbon-based molecules, such as hydrocarbons, pesticides, etc. (Schaeffer et al. 2016; FAO and UNEP 2021). In recent years, countless emerging pollutants such as electronic waste, nanomaterials, pharmaceuticals, personal care products, etc. also found their way into the environment and pollute the soil (Fig. 15.1).

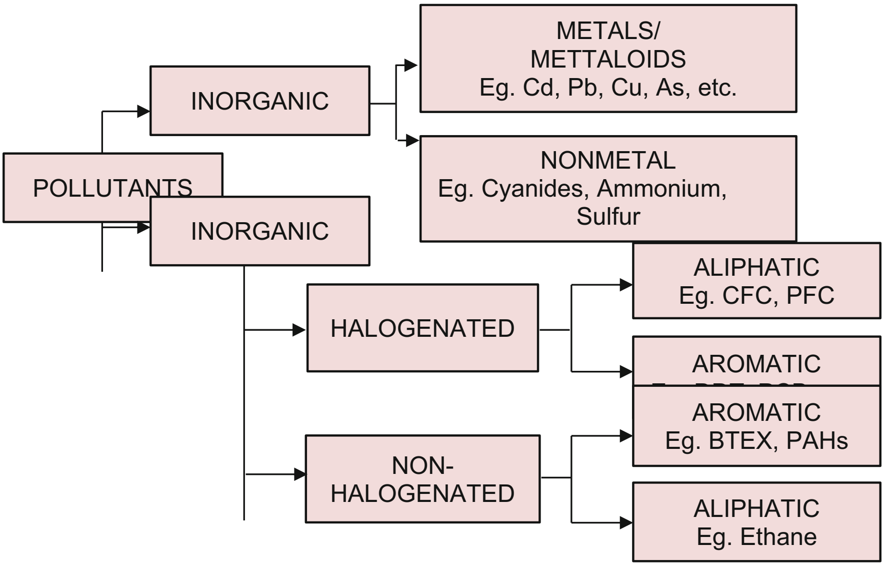

**Fig. 15.1** Classification of different types of soil pollutants (FAO and UNEP 2021)

## 15.2 Kinds of Pollutants

### 15.2.1 Heavy Metals

In soils, heavy metals are naturally present because of geologic and pedogenic processes during weathering of parent materials and are rarely found beyond toxic limit. When excessive quantities are present due to anthropogenic processes, they have detrimental effect on plants and other living beings. Essential plant nutrients such as zinc (Zn), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo) and nickel (Ni) are required by plants in very low quantities to complete their cycle, whereas vanadium (V), selenium (Se), and cobalt (Co) are considered as beneficial elements. Other heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), tin (Sn) and metalloid such as arsenic (As) and antimony (Sb) do not have any beneficial role in plants. They are highly persistent, toxic and nonbiodegradable and pose severe environmental hazard (Yang-Guang et al. 2016). When these elements are present at high concentration, it deleteriously affects the morphology, physiology and biochemistry of crop plants, thereby causing reduction in growth and yield (Chatterjee and Chatterjee 2000; Oancea et al. 2005). Harmful effects of heavy metals on different crop plants are summarized in Table 15.1. In addition, consumption of plants grown in heavy metal polluted soils will transfer heavy metals from soil to plants and then to animal and human life, resulting in biomagnification (Intawongse and Dean 2006). Heavy metal uptake by plants from soil is a function soil properties and dynamics of heavy metal in the soil (Blaylock and Huang 2000; Zwolak et al. 2019).

Heavy metals in soils originate from various sources, among which anthropogenic activity is the main source. Anthropogenic activities such as fossil fuel combustion, mining, metallurgical processes, municipal sewage and sludge, power plants, etc. increase the risk of heavy metal pollution (Alloway 1990). Agriculture also largely contributes to heavy metal pollution through fertilizers and manures, pesticides, irrigation with sewage water, and land application of sewage sludge (Gimeno-Garcia et al. 1996; Srivastava et al. 2017). Phosphate fertilizers and some micronutrient fertilizers are often known to contain impurities such as Cd, Cr, Ni, Pb, Co, Cu and Zn (Gimeno-Garcia et al. 1996). Pesticides are often contaminated by Cr, Co, Cd, Fe, Mn, Zn, Pb and Ni (Gimeno-Garcia et al. 1996; Defarge et al. 2018). Untreated sewage water and sludge contain high concentration of Cr, Cu, Zn, Pb, Ni, Hg and Cd (Sharma et al. 2004; Huang and Yuan 2016; Agoro et al. 2020), while animal manure may be a source of Cu, Zn, As, Cr, Cd and Pb (Zhang et al. 2012). Through these contaminated amendments, heavy metals may find their way to agricultural soil. However, the risk of metal buildup would depend on soil properties, composition and application rate of amendments. Higher content of available forms of Cu, Zn, Mn, Cd, Ni and Pb is reported from soil regularly amended with manures and fertilizers (Sienkiewicz et al. 2009; Wei et al. 2020).

**Table 15.1** Toxicity effects of heavy metals on pants

| Heavy metal | Plants | Toxic effect in plants | Reference |
|---|---|---|---|
| As | *Oryza sativa* | Reduce root biomass and yield | Das et al. (2013) |
| | *Zea mays* | Reduce root and shoot length | Duquesnoy et al. (2010) |
| | *Leucaena esculenta* | Reduce shoot length, leaf area, shoot dry weight, seeds per pod, seed yield, photosynthesis rate | Talukdar (2013) |
| Cd | *Oryza sativa* | Reduce seed germination, growth, mineral nutrients uptake, photosynthesis and grain yield, cause oxidative stress and genotoxicity | Rizwan et al. (2016) |
| | *Oryza sativa* | Impair yield formation and grain quality by altering yield components | Kanu et al. (2017) |
| | *Triticum aestivum* | Reduce root elongation, dry mass production, plant height and number of tillers per plant | Zhang et al. (2000) |
| | *Pisum sativum* | Minimize seed germination and inhibit plant growth | Baruah et al. (2019) |
| Co | *Vigna radiata* | Reduce antioxidant enzyme activities, sugar content | Jayakumar et al. (2008) |
| | *Phaseolus vulgaris* | Decrease yields, leaf chlorosis | Wallace et al. (1977) |
| Cr | *Vigna radiata* | Reduce germination percentage and bud sprouting | Rout et al. (1997) |
| | *Citrullus lanatus* | Disturbs nutrient balance | Dube et al. (2003) |
| | *Oryza sativa* | Reduce uptake of Zn, cu, Fe, K, P and N | Sundaramoorthy et al. (2010) |
| Hg | *Medicago sativa* | Retard growth and development; disrupt cellular functions | Aydinalp and Marinova (2009) |
| | *Zea mays* | Reduce root elongation, stunted growth | Patra et al. (2004) |
| | *Oryza sativa* | Enhance as(III) toxicity to rice seedling | Ren et al. (2014) |
| Cu | *Phaseolus vulgaris* | Damage root malformation and growth inhibition | Cook et al. (1997) |
| | *Hordeum vulgare* | Reduce net photosynthetic rate and photosynthetic capacity | Vassilev et al. (2002) |
| | *Chloris gayana* | Root cuticle disruption and reduce root hair proliferation | Sheldon and Menzies (2005) |
| Pb | *Elsholtzia argyi* | Inhibit seed germination, adversely affect the length of radical and hypocotyl | Islam et al. (2007) |
| | *Raphanus sativus* | Growth depression with interveinal chlorosis, reduce nutrient absorption | Gopal and Rizvi (2008) |
| | *Oryza sativa* | Hampers germination, root/shoot length, growth and final yield; reduces nutrient uptake; disrupts chloroplast ultrastructure and cell membrane permeability | Ashraf et al. (2019);<br>Hossain et al. (2015) |

(continued)

**Table 15.1** (continued)

| Heavy metal | Plants | Toxic effect in plants | Reference |
|---|---|---|---|
| Zn | *Oryza sativa* | Inhibition of root growth, leaf chlorosis, reduce shoot and root biomass | Song et al. (2011) |
| | *Triticum aestivum* | Decrease plant growth, yield and level of reactive oxygen species | Kanwal et al. (2016) |
| | *Brassica chinensis* | Low chlorophyll content, chlorosis | Yang et al. (2012) |
| Mn | *Arabidopsis thaliana* | Inhibit root elongation, reduce uptake and translocation of ca, mg, Fe and P | Lešková et al. (2017) |
| | *Vigna umbellata* | Inhibit chlorophyll biosynthesis | Subrahmanyam and Rathore (2001) |
| Fe | *Oryza sativa* | Poor growth and tillering, severe yield reductions | Suriyagoda et al. (2020); Audebert and Fofana (2009) |
| | *Phaseolus vulgaris* | Reduce germination and root/shoot ratio | El Rasafi et al. (2016) |
| | *Triticum aestivum* | Inhibit germination, reduce root length | El Rasafi et al. (2016) |
| Ni | *Oryza sativa* | Chlorosis and necrosis, reduce fresh weight and length of roots and shoots, protein contents; increase ROS and lipid oxidation | Samantaray et al. (1997); Ruchi and Dubey (2009) |
| | *Populus nigra* | Decrease stomatal conductance | Velikova et al. (2011) |
| | *Triticum aestivum* | Reduce plant nutrient acquisition | Pandolfini et al. (1992) |
| | *Solanum tuberosum* | Retard plant growth, reduce chlorophyll and Fe and Zn contents | Shukla and Rajeev (2009) |

### 15.2.2 Radionuclides

Radioactive forms of elements are called radionuclides. Some radionuclides occur naturally in non-radioactive ores in the environment, and their presence is either cosmogenic or terrestrial (Smičiklas and Šljivić-Ivanović 2016). Cosmogenic radionuclides may not pose serious threats to humans and animals as their radiation is much lower. In general, natural background radiation contributes 79% of exposure in man, while man-made radiation sources such as x-rays and nuclear medicine contributes 19%, and 2% is contributed by nuclear weapon tests and nuclear reactor accidents (Wild 1993). Global fallout through accidental releases, nuclear weapons testing and faulty radioactive waste disposal are responsible for radioactive contamination of many soils and may render the soil unproductive and sterile (Zhu and Shaw 2000). Low plant population and higher cytogenetic disturbances and genetic diversity characterize radioactive pollution of soil (Geras'kin et al. 2005). Radionuclide concentration in wild plants and soil collected after Fukushima Daiichi nuclear disaster in 2011 was very high (Mimura et al. 2013). Due to increase in accidental and routine releases of radionuclides from the nuclear industry, mining and processing of ores, etc., there is a growing concern to remediate radioactively contaminated sites (Zhu and Shaw 2000).

### 15.2.3 Asbestos

Asbestos (amosite, chrysotile, crocidolite, tremolite, anthophyllite and actinolite) and asbestos-containing materials are widely used as construction materials (Godish 1989). Due to their flexibility, high tensile strength, resistance to heat, chemicals and fire, it found several use in industries (Virta 2005). As asbestos-containing wastes are generally disposed in combination with building material matrix, the volume of landfill site required is generally huge. Abrasive action and wear and tear in the waste pile may lead to asbestos fibre exposure via air, soil and water (Mohanty et al. 2021). Leachates from these landfills are also a potential source of heavy metal pollution (Promentilla and Peralta 2003). Asbestos fibres in air when inhaled cause mesothelioma, asbestosis and lung cancers. They also hamper plant growth and development by reducing foliar nutrient status (Trivedi and Ahmad 2011). Soils containing asbestos as low as 1% (by weight) can generate hazardous levels of exposure when disturbed due to abrasive action and get transported elsewhere (Carlin et al. 2015). Thus, the importance of remediating soils contaminated with asbestos cannot be overstated.

### 15.2.4 Organic Pollutants

Soil organic pollutants (OPs) are of great concern due to their xenobiotic nature, toxicity and persistence. They enter the soil through oil spills and leaks, petrochemical industries, pharmaceuticals, agrochemical inputs, etc. They have mutagenic effect on microorganisms even at very low concentrations and disrupt the soil biological, physical and chemical processes, thereby hampering nutrient mobility (Saha et al. 2017). The most common OPs found in soils are described in the following section.

Oil hydrocarbons such as alkanes, alkenes, cycloalkanes, etc. originated from crude oil and natural gas, the two most common petroleum hydrocarbon contaminant of soils (Ellis and Adams 1961). Pipeline leaks are a major contributor of crude oil and natural gas pollution, and the past decade has seen several accidental or intentional release of petroleum pollutants into the environment (Timmerman 1999). Their adverse effect on soil and organism depends on the soil and hydrocarbon characteristics. Petroleum hydrocarbons are known to dissolve membrane lipids, thereby reducing microbial diversity and evenness in soil (Mukherjee et al. 2014; Ball and Truskewycz 2013). They disturbed the microbial structure in soil, inhibiting many soil enzymes involved in N, P, or C transformation (Labud et al. 2007). Plants grown in oil-contaminated soil exhibited phytotoxic symptoms, which are visible from reduced germination, root length and leaf area, among many others (Rahbar et al. 2012; Ilyas et al. 2021).

Halogenated hydrocarbons are those hydrocarbons in which the H in aliphatic or aromatic hydrocarbons is replaced with a halogen such as fluorine (F), chlorine (Cl), bromine (Br), or iodine (I). Aliphatic halogenated hydrocarbons include chloroform, $CCl_4$, CFCs, alkyl halides, vinyl chloride, phosgene, hexachlorocyclopentadiene, chlorohydrins, chlorinated paraffins, insecticidal aliphatic and alicyclic cyclodienes, chlorinated pyrethroids and chlorpyriphos. Aromatic halogenated hydrocarbons are polychlorinated biphenyls (PCBs), polychlorinated dibenzodioxins (PCDDs), polychlorinated dibenzofurans (PCDFs), etc. (Safe 1990). These compounds are found in biocides, degreasers, plastics, electrical insulators, industrial solvents, fumigants, paint, printing ink, flame retardants, refrigerants, etc. (Häggblom and Bossert 2003). Many of these compounds are xenobiotic, persistent and highly toxic and often called persistent organic pollutants (POPs) (Chaudhry and Chapalamadugu 1991). These compounds are highly recalcitrant and resist biodegradation as they contain at least one electronegative halogen atom that makes them very stable (Mohn 2004; Nikel et al. 2013). Their hydrophobicity increased their adsorption by soil particles, thereby reducing their bioavailability for biodegradation (Häggblom and Bossert 2003).

Polycyclic aromatic hydrocarbons (PAHs) encompass diverse organic compounds with two or more fused benzene rings (Huang and Penning 2014). Light-molecular-weight PAHs (two to three aromatic rings) occur in the atmosphere in gaseous phase, whereas high-molecular-weight PAHs (four or more aromatic rings) bind on a surface (Lee and Vu 2010; Patel et al. 2020). Some common PAHs are naphthalene, acenaphthylene, acenaphthene, phenanthrene, anthracene, pyrene, benz(a)anthracene, etc. They are produced during incomplete combustion of forest and bush fires, fuel and coal combustion, cigarette smoke, accidental spillage of crude oils, etc. (Abdel-Shafy and Mansour 2016). The recalcitrant and persistent nature of PAH is due to high lipophilicity, hydrophobicity and thermostability (Patel et al. 2020). They found their way to soils through dry or wet deposition or fill materials containing PAHs (Abdel-Shafy and Mansour 2016). A soil is considered polluted when total PAHs exceed 200 ng $g^{-1}$ (Wu et al. 2019a, b). In soil, PAHs with three or more rings tend to be adsorbed strongly to the soil particles, whereas light-molecular-weight PAHs are absorbed by plant roots and transported to the biomass depending on soil texture and organic matter content (Oleszczuk and Baran 2004). The effect of PAHs on soil properties includes choking of soil pores, reduced aeration and water infiltration; and the intensity is governed by soil texture, pH and soil organic matter content (Sakshi et al. 2019). Phytotoxicity depends on the type of PAHs, their derivatives, plants species and soil properties, and symptoms generally reported include inhibition of seed germination and growth, chlorosis, late flowering, necrosis, oxidative stress, etc. (Edwards 1983; Henner et al. 1999, Marwood et al. 2001; Alkio et al. 2005). Some reports suggest pronounced toxicity of their derivatives or photomodification of parent compounds (Huang et al. 1997; Paková et al. 2006).

Volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs) encompass organic pollutants that can vaporize and enter the environment at room temperature (vapour pressure ≥ 0.01 kPa at 20 °C) although there is no strict distinction between them (Yadav and Pandey 2018; Lei et al. 2021; Li et al. 2021). Commonly found VOCs include monomeric aromatic hydrocarbons (benzene, toluene, ethyl benzene and xylene, collectively called BTEX, which are easily biodegradable) and halogenated hydrocarbon such as chloroethylene, trichloroethylene, etc. They are found in many products such as cosmetics, fuel oils, paints, solvents, dry cleaning reagents, combustion exhausts, etc. (Li et al. 2021). Their volatile nature makes them mobile and can travel long distance (ATSDR 2005). They enter the soil as vapour or liquid when VOCs or products containing them are released into the environment (Yadav and Pandey 2018). Their behaviour in soil is a function of adsorption properties of soil, moisture content, permeability, porosity, surface area, etc., and high moisture content effectively reduces its adsorption to soil particles (Delle Site 2001; Rivett et al. 2011). VOCs in the atmosphere reportedly cause chlorosis, reduced shoot and root growth, decreased leaf area, defoliation and fruit abscission in plants (Cape 2003).

### 15.2.5 Emerging Pollutants

Emerging pollutants (EPs) comprise of synthetic chemicals that are released into the environment daily for which no guidelines or control measures are currently established and are considered highly toxic even at very low concentrations (Smital 2008). They allegedly have serious detrimental effect to plant and animal life, but information in this regard is scanty (Gomes et al. 2017). It includes electronic waste, nanomaterials, pharmaceuticals and industrial compounds such as bisphenol A, nonylphenols, etc. These pollutants may enter the soil though the land application of sewage sludge containing EPs or atmospheric deposition.

Electronic wastes or e-wastes are wastes generated from discarded electronic and electrical devices such as television, computer, mobile phone, etc. It is estimated that 53.6 Mt. of e-waste was generated in 2019, and it is expected to rise to 74.7 Mt. by 2030 (Forti et al. 2020). One important factor for rapid rise in e-waste worldwide is the short life span of electronic devices (Widmer et al. 2005). These devices contain hazardous materials in their circuit boards, and their recycling and disposal becomes a serious concern. Common pollutants found in e-waste include toxic heavy metals and metalloids such as Ba, As, Be, Cd, Co, Cr, Cu, Fe, Pb, Hg, Ni and Zn and POPs such as PAHs, PCDD/PCDFs, PBDEs, etc. (Widmer et al. 2005; Shi et al. 2019; Kiddee et al. 2020). Dismantling or recycling of e-waste produces broken particles, residue and dust that pollute the local environment (Cesaro et al. 2019). Unsafe disposal in landfills may cause leaching of the toxic heavy metal and organic pollutants.

Nanomaterials (NMs) are either natural or engineered objects that have at least one of its dimensions in the range of 1 to 100 nm. There are several classes of nanomaterials: carbon nanomaterials such as fullerenes, graphenes, nanodiamonds, etc.; metal nanomaterials such as metal oxides ($TiO_2$, ZnO, $CeO_2$, etc.), quantum dots and inert metals (Fe, Ag and Au); and dendrimers or multifunctional polymers (Klaine et al. 2008). They have several applications in medicine, engineering, agriculture and marine-related activities. Despite the many advantages, uncontrolled release and unsafe disposal present new risks and uncertainties for the environment. Their presence has been detected in air, waterbodies, soils and tissues of plants and animals (Gupta and Xie 2018; Rai et al. 2018; Rajput et al. 2020). They enter the soil though application of nanoproducts: spill and disposal of waste containing nanoparticles (Gladkova and Terekhova 2013; Zuin et al. 2003). These scenarios give grounds to consider them as emerging pollutants (Gladkova and Terekhova 2013; Rajput et al. 2020). Once they reached the soil system, their fate and toxicity depend on the adsorption and desorption with soil particles, oxidation and reduction reactions and aging (Loureiro et al. 2018) Phytotoxity symptoms include growth inhibition, reduced root and shoot length, low germination rate, oxidative stress, etc. (Parthasarathi 2011).

Pharmaceutical products are introduced into the soil during their production, use and disposal and during soil application of municipal effluents and biosolids containing pharmaceuticals (Gworek et al. 2021). Presence of antibiotics, analgesic, anti-inflammatories and psychiatric drugs has been reported from many soils irrigated with reclaimed urban wastewater (Kinney et al. 2006; Biel-Maeso et al. 2018). Phytotoxicity of antibiotics by many crop plants has been reported. Low concentration of oxytetracycline severely inhibits shoot and root growth of *Medicago sativa* by 61 and 85%, respectively (Kong et al. 2007). Growth reduction in *Daucus carota* was observed when grown in soil containing 6–10 ppm of ciprofloxacin, metformin and narasin (Eggen et al. 2011). Antibiotics such as sulfadiazine, sulfadimidine and enrofloxacin have inhibitory effects on root and shoot elongation in cabbage and tomato (Jin et al. 2009). The toxicity and accumulation of pharmaceuticals in soil are a function of the active ingredient and their degradation, adsorption, transport and soil properties (Du 2012).

## 15.3 Strategies for Remediation of Polluted Soils

The release of contaminants to soil affects its physical, chemical and biological properties, thereby reducing its functioning capacity. The objective of any soil remediation measure is to restore the polluted soil by reducing the concentration of pollutants to a level prior to disturbance, convert them into less hazardous forms, or prevent their spread in the environment. Polluted soil may be remediated using various strategies. These strategies are classified based on the process involved (physicochemical, biological, electrical, or thermal), objective (containment or clean-up), or location of remediation (in situ or ex situ) (Shackelford 2013). One remediation technique may belong to one or more class. Physicochemical remediation techniques involve the use of physical process and/or chemical reaction (Koul and Taak 2018). Biological strategies use living beings such as microbes and plants to contain or clean up contaminated sites. Thermal remediation uses different sources of heat to subject contaminants to high temperature. Containment refers to storing of polluted soil with covers and barriers to prevent their migration in other areas. In clean-up strategies, the total concentration of pollutant is reduced to an acceptable level (Lombi and Hamon 2005). Remediation may be situated at its original location (in situ) or excavated and treated elsewhere (ex situ) (Liu et al. 2018b).

## 15.3.1 Physicochemical Methods

The physicochemical methods of polluted soil remediation include techniques such as landfilling, excavation and off-site disposal of polluted soils, surface capping, encapsulation, soil washing (solvent extraction), soil flushing, solidification, stabilization, soil vapour extraction, chemical dehalogenation, separation-fractionation and photo-oxidation, among others.

### 15.3.1.1 Landfilling

Solid waste disposal in landfills remains the simplest, most economic and attractive soil remediation technique (Liu et al. 2018b). Wastes undergo physical, chemical and biological transformations in this method (Nanda and Berruti 2021). Landfill site selection is an important issue in waste management and depends on climate, topography, soil type, distance from habitation and cost of transportation of waste from contaminated site. The efficiency of landfilling rests on technical design, construction, and economic and legal framework (Liu et al. 2018b; Osazee 2021). The main disadvantages of this method are that it became a source of health and environmental hazard if leachates and unwanted gases leaked from the landfills.

### 15.3.1.2 Excavation and off-Site Disposal of Polluted Soils

This involves excavation of inorganic and organic pollutants from polluted sites followed by ex situ treatment or off-site disposal to a landfill (USEPA 1996). Transport of excavated soil required precautions to avoid secondary exposure. This method merely relocates the problem from one site to another without any treatment (Lombi and Hamon 2005).

### 15.3.1.3 Surface Capping

It is a low cost in situ method in which surface of polluted sites or landfill is capped with a waterproof material or material with low permeability to prevent the spread of pollutants from contaminated sites to the adjacent uncontaminated sites (Evanko and Dzombak 1997; Ossai et al. 2019). It is not remediation measure per se as it does not reduce, destroy, or decrease toxicity of pollutants in the soil (Liu et al. 2018b). Capping materials include high-density polyethylene (HDPE) liners, synthetic membranes, asphalt, cement and low-permeability soil such as clay (USEPA 1996). The main disadvantage of this method is that the capped surface may not support any vegetation.

#### 15.3.1.4 Encapsulation

Encapsulation is a containment technique similar to surface capping. Low-permeability caps, slurry walls, underground barriers, barrier floors, grouting method, or cutoff walls are constructed to prevent spread of contamination (Chakrabartty and Harun-Or-Rashid 2021). These layers reduce the infiltration and percolation of the precipitation and stop leaching and migration of pollutants from the contaminated area (Anderson and Mitchell 2003). This technique merely prevents the contaminants from spreading and does not remove contaminants from soil grains. It is not a permanent remedy of contaminant, and its efficiency decreases with the passage of time.

#### 15.3.1.5 Soil Washing (Soil Flushing)

Soil washing and soil flushing are often used interchangeably. They are physico-chemical remediation processes that use a solvent to remediate soils polluted with radionuclides, organic and inorganic pollutants. Soil washing is used in the case of ex situ remediation in which polluted soils are excavated, crushed and homogenized, followed by chemical leaching with solvents to remove pollutants from soil (Rodríguez et al. 2014; Liu et al. 2021). Soil flushing is an in situ method to remove contaminants from soil by injecting or infiltrating washing fluid that enhanced mobilization of contaminants. The washing solutions mobilize the pollutants by changing the pH, solubility, or mobility or by chelation. The success of this technique depends on soil properties, types of pollutants in soils, washing agent, concentration and soil-solvent ratio (Liu et al. 2021). Effective solvents include inorganic salts (NaOH, $Na_2CO_3$, $CaCl_2$, NaCl $FeCl_3$, etc.), mineral acids (HCl, $H_2SO_4$, $HNO_3$, $H_3PO_4$), complexing agents (EDTA, EDDS, DTPA, acetic acid, oxalic acid, etc.), natural or biosurfactants (saponin, chitosan, tannic acid, rhamnolipids cyclodextrin), etc. (Moutsatsou et al. 2006; Alghanmi et al. 2015; Zhu et al. 2015; Bilgin and Tulun 2016; Yang et al. 2017; Nejad et al. 2018; Liu et al. 2021). Feng et al. (2021) reported that batch extraction soil flushing with deionized water could extract only 20% Cu and 30% Cd. Addition of electrolytes (NaCl, $CaCl_2$) and chelating agents (EDTA) enhanced the extractions to about 60–90% and $>$ 99%, respectively. Sequential soil flushing with citric acid followed by a surfactant removes 85.6% Zn, 62% Pb and 31.6% of heavy petroleum oils from a contaminated site (Yun et al. 2015). Chitosan (pH 3.3) has better extraction efficiency of Cu (43.4%) and Ni (37.1%), compared with EDTA (pH 3.1) (Jiang et al. 2011). Wuana et al. (2010) reported that EDTA is a superior washing solution to citric acid and tartaric acid. Reddy et al. (2011) reported maximum metal removal (25–75%) in 0.2 M EDTA, whereas maximum PAHs were removed from surfactant-enhanced system. Gitipour et al. (2014) reported that the cresol removal efficiencies of sodium dodecyl sulphate and Triton X-100 were higher at higher concentrations in alkaline pH, whereas at similar concentrations and pH of surfactants, sodium dodecyl sulphate has higher removal efficiency than Triton X-100. The pollutants in washing solution are treated (photocatalysis, ozonation, electrochemical and biological processes) and reused or disposed of safely (Liu et al. 2018b). The tendency of contaminants to spread to other uncontaminated areas may limit the application of this technique.

#### 15.3.1.6 Soil Vapour Extraction

Soil vapour extraction (SVE) is an in situ technology to remediate VOCs and some SVOC pollutants such as phenol and naphthalene in unsaturated zone (vadose zone). In this remediation technique, vacuum is applied to the polluted soil through pressure venting wells to create negative pressure that enhances the evaporation and desorption of the most volatile constituents toward these wells (Simpanen 2016). The off-gases containing the pollutants are treated by pyrolysis or photo-oxidation (Lombi and Hamon 2005; Rodríguez et al. 2014). The effectiveness of SVE depends on the number and spacing of extraction wells, soil-gas extraction rate, temperature, moisture content, clay content, air permeability and organic matter content of soil and vapour pressure and solubility of the contaminants (Sellers 1998; Qin et al. 2009; Albergaria et al. 2012). These factors may be modified in the SVE systems to enhance the extraction. Remedial techniques such as air sparging, bioremediation, bioventing, steam injections, or radiofrequency heating may be used in combination with SVE to enhance extraction efficiency (Qin et al. 2009; Soares et al. 2010). Integration of bioventing and SVE improves toluene removal efficiency to more than 99.5% (Amin et al. 2014a, b). Cho et al. (2006) could remove 55% of TPH and 98% of benzene from jet fuel-contaminated site when SVE is coupled with biodegradation.

#### 15.3.1.7 Solidification

Solidification involves introduction of binding materials to trap contaminants into a stable solid block, thereby reducing the bioavailability and leachability of contaminants and preventing its migration and exposure (Rodríguez et al. 2014). Binding materials include bitumen, asphalt, cement, polyethylene, clays, quicklime, geopolymer, etc. (Lombi and Hamon 2005; FRTR 2012). Although this technique is considered primarily applicable to radionuclides and inorganic pollutants, it was successfully applied for remediation of soils contaminated with organic pollutants too (Rodríguez et al. 2014). Navarro-Blasco et al. (2013) reported that calcium aluminate cement mortar fully retained Cu and Pb, while Zn retention was 99.99%. Magnesium silicate hydrate solidification of radionuclide Cs gives satisfactory leaching rate and cumulative leach fraction (Zhang et al. 2020). The limited use of solidification technique in remediation of organic pollutants was due to leaching from the matrix. However, use of suitable adsorption-enhancing additive such as powdered activated carbon significantly reduced this problem (Sörengård et al. 2021). The longevity of stabilized mass depends on the weatherability and water infiltration.

#### 15.3.1.8 Chemical Immobilization

This technique reduces the solubility or chemical reactivity of a pollutant into a nontoxic form using immobilizing agents. Immobilizing agents include lime, phosphate, fly ash, compost, biochar, activated charcoal, carbonates, phosphates, clays and alkalis. These stabilizing agents use various mechanisms such as precipitation, immobilization, complexation, redox reactions, ion exchange, pH alteration and electrostatic interaction to chemically stabilized pollutants in soil, reducing the mobility and phytoavailability of pollutants (Lombi and Hamon 2005; Kumpiene et al. 2008; Rodríguez et al. 2014; Xu et al. 2020). Addition of C-rich materials to tannery soil effectively reduced $Cr^{+6}$ to $Cr^{+3}$, thereby reducing the phytotoxicity of Cr in *Brassica juncea* (Choppala et al. 2015). Alkaline organic treatments of smelter sites resulted in largest reductions in extractable Cd, Pb and Zn, thereby reducing phytotoxicity to *Lactuca sativa* L. (Basta et al. 2001). The presence of phosphate stabilized Zn, Pb and Cd in soil, thereby reducing total leachable metal (Kribek et al. 2019). Addition of sepiolite increased the soil pH, converting the exchangeable fraction of Cd and Pb to non-exchangeable Fe-Mn oxide, thereby reducing its phytotoxicity (Sun et al. 2013). The drawback of remediation through stabilization is its limitation for use in soils polluted with several elements with diverse chemistry.

#### 15.3.1.9 Chemical Dehalogenation

Halogenated hydrocarbons are highly persistent and toxic. Chemical dehalogenation is an ex situ remediation method that aims to remove halogens from halogenated organic pollutants to render them less toxic or innocuous. Two main processes employed for chemical dehalogenation are base catalyzed decomposition (BCD) and alkaline polyethylene glycol (APEG) (USEPA 1996). In this process, contaminated soils are sieved to remove large rocks and debris. BCD involves thermal desorption at temperatures ranging from 315 to 426 °C with the addition of $NaHCO_3$ to the contaminated soil, followed by catalytic dehalogenation. In APEG, potassium polyethylene glycol replaced the halogen to render the compounds non-hazardous glycol-ethers and alkali metal salts water-soluble salts.

BCD is mainly used to dehalogenate PCBs, dioxins and furans, whereas halogenated aliphatic compounds are dehalogenated using APEG method. Chemical dehalogenation may be combined with other remediation technologies to improve extraction efficiency. The extraction efficiency of dehalogenation depends on kinds of chemicals, rate and time of milling, temperature, extractant/soil ratio, PEG chain length and catalyst (Xu and Bhattacharyya 2007; Nah et al. 2008; Zorrilla et al. 2015). Zorrilla et al. (2015) reported that the best destruction and removal efficiency of PCBs (88.5%) was obtained at KPEG/oil ratio of 30 and PEG 600. Under experimental conditions, maximum removal efficiency (99%) of PCBs was observed at 150 °C for 4 h using PEG 600, KOH and Al in transformer oil-contaminated soil (Ryoo et al. 2007). Fine metal powder catalysts Zn, Fe, Al and Mg show 70, 55, 30 and 31% PCB removal; long-chain PEG200 was more effective than short chain such as triethylene glycol and ethylene glycol; total Cl concentration in oil decreased significantly from 1343 ppm to 89 ppm within 4 h (Nah et al. 2008). Catalysts such as Rh, Ru, Au, Pt, Pd and Ni may also be added to lower the activation energy (Xu and Bhattacharyya 2007; Yoneda et al. 2008; Akzinnay et al. 2009; Ma et al. 2010; Amorim and Keane 2012; Gómez-Quero et al. 2013; Molina et al. 2014). Though catalytic dehalogenation is a promising remediation technique owing to clean, relatively cheap and efficient technique (Molina et al. 2014), it is still difficult to apply in extremely polluted soils or large area because of excessive amounts of reagents required, which makes it uneconomical (Lombi and Hamon 2005).

### 15.3.1.10 Chemical Oxidation-Reduction

It is used as both in situ and ex situ technology and involves mixing of strong oxidizing agents such as $O_3$, $H_2O_2$, $MnO_4^-$, $Na_2S_2O_8$, etc. to oxidize pollutants in contaminated soils to promote abiotic oxidation of pollutants into innocuous products (Russo et al. 2010). One of the biggest challenges in the application of this technology is the selection of oxidant, optimum dosage and suitable catalysts and/or additives (Ranc et al. 2016). Gaseous $O_3$ oxidizes organic contaminants either directly by ozonation or indirectly by producing strong radicals such as $\bullet OH$, $\bullet HO_2$, $O^{2-}$, $O^{3-}$, etc. and is generally used as acidic medium (Russo et al. 2010). $H_2O_2$ produce $\bullet OH$ radicals in the presence of $Fe^{2+}$, which can react with most organic contaminants due to its nonselective nature, and require acidic media (pH 2–4) (Rivas 2006). $MnO_4^-$ oxidizes organic compounds containing $C{=}C$ double bonds, aldehyde groups, or hydroxyl groups (Russo et al. 2010). The effectiveness is governed by state of the contaminants, choice of oxidant and dosage, pH of the medium, etc. Various studies reported that oxidation with $KMnO_4$ was more efficient in removing PAHs from contaminated soil than Fenton-like reagent, activated persulfate or $H_2O_2$ (Brown et al. 2003; Zhao et al. 2011; Boulangé et al. 2019). One major disadvantage of this technology is that oxidants adversely affect indigenous microbial diversity, destroy microbial population and enhance organic matter oxidation (Liao et al. 2019; Xu et al. 2020). Sulphate radical advanced oxidation with chelating agent and surfactant optimized the efficiency of PAH extraction with lesser soil organic matter destruction (Xu et al. 2020). A recent study showed that in situ chemical oxidation may be used as a pre-treatment for bioremediation to enhance clean-up of contaminated soil (Sutton et al. 2011).

### 15.3.1.11 Activated Carbon

Activated carbon (AC) is an amorphous solid and a porous and highly carbonaceous material. It has high surface area and adsorption capacity, non-polar, usually prepared in small pellets or a powder (Vasilyeva et al. 2006). It is used as an in situ treatment technology to remediate soils and water polluted with organic and inorganic pollutants (USEPA 1996). Polluted soil remediation by this technique employs adsorption that retards the contaminant movement and degradation through other remedial measures (Fan et al. 2017; USEPA 1996). The efficiency of this technique depends on dosage, type of pollutants, soil properties and time of exposure (Kołtowski et al. 2016). Kołtowski et al. (2016) reported that AC or biochars reduce the bioavailability of pollutants and reduce its toxicity on *Lepidium sativum*. ACs also effectively reduce the bioaccumulation of PCBs and PAHs (Zimmerman et al. 2004; Millward et al. 2005), DDT (Tomaszewski et al. 2008), PCDDs and PCDFs (Josefsson et al. 2012), pharmaceuticals and personal care products (Nam et al. 2014a, b), and organochlorine pesticides (Dang et al. 2018). AC-based remediation reduces the phytotoxicity of PCBs, thereby creating better conditions for bioremediation (Vasilyeva et al. 2010). However, AC application under field condition is often limited by their high buoyancy, for which AC clay granules can be used and was found to reduce PCB-bioaccumulation of up to 89% (Abel and Akkanen 2019).

## 15.3.2 Thermal Remediation Techniques

Thermal remediation uses heat to volatilize or destroy contaminants by thermal desorption, incineration, vitrification, pyrolysis, radiofrequency and microwave heating, steam and hot air injection and smouldering combustion (Vidonish et al. 2016).

### 15.3.2.1 Thermal Desorption

Thermal desorption (TD) is a clean-up technology that uses heat to volatilize the most VOCs and SVOCs and desorb them from the contaminated soil (Kastanek et al. 2016). It is very efficient with a short treatment period (Zhao et al. 2019). In this technique, contaminated soils are heated at an appropriate temperature to evaporate VOCs and SVOCs that are eventually recovered or destroyed (Zhao et al. 2019). In general, VOC requires lower temperature, whereas SVOCs and volatile metals require high-temperature thermal desorption. The efficiency of this technique is affected by nature of the contaminant, its concentration, soil properties, heating conditions, and carrier gas (Zhao et al. 2019). Thermal treatment of PCBs at 600 °C for 1 h attained removal efficiency of 98.0%. Desorption at above 300 °C achieved removal efficiencies above 99.7% in PAH-contaminated soil (Renoldi et al. 2003). With rising TD temperature, the residual amount of PCBs decreases, and dechlorination and decomposition increases (Qi et al. 2014). Removal of more than 99.8% of elemental Hg was reported at temperatures ranging from 244 to 259 °C in sand matrices (Kunkel et al. 2006). The lowest values of Hg in treated samples were obtained at a higher temperature (700–800 °C) and exposition time (6 h) (Navarro et al. 2014). However, this technology becomes uneconomical when high temperatures (>600 °C) are involved, and it also renders the soil unusable for agricultural purpose (He et al. 2017). In addition, chloridizing agents ($FeCl_3$) could improve removal efficiency of Hg at 400 °C (He et al. 2017). Solar energy may also be used as the primary energy source during TD and was successfully used in removing Hg and As from polluted soil (Navarro et al. 2014). One major shortcoming of TD is deterioration in soil fertility and loss of some functional propertied at high desorption temperature (Lee et al. 2021).

### 15.3.2.2 Incineration

Incineration is an ex situ thermal remediation in which very high temperature (870–1200 °C) is employed to volatilize and combust organic pollutants by thermal oxidation. In this method, polluted soils are excavated and transferred to an off-site incinerator (Lombi and Hamon 2005). Although it is an effective method to destroy various contaminants, the use of incineration as a remediation technique limited by high cost involved, which makes it uneconomical when high temperature is involved, and it does not destroy heavy metals (Kristo 2020). Another apprehension is that it may release carcinogenic and toxic chemicals such as volatile metals, VOCs, and SVOCs in the air (Wikstrom and Marklund 2000; McKay 2002; Conesa et al. 2005). A low-temperature (500–700 °C) two-stage fluidized bed incineration could remove heavy metals and 98.3–99.9% of lube oil in treated soil (Samaksaman et al. 2016). At 900 °C, thermal incineration removes more than 90% of TPH in oil-contaminated soil (Weng et al. 2020).

#### 15.3.2.3 Vitrification

Vitrification is heat treatment of contaminated soil at extremely high temperatures (>1500 °C) through a powerful source of energy (fossil, electrical, thermal or plasma) to convert polluted soil into a stable, inert vitreous material that entraps pollutants (Rodríguez et al. 2014; Liu et al. 2018b). Additives such as glass formers and glass modifiers may be added to enhance the encapsulation. In general, electrical and plasma vitrifications are used as in situ remediation techniques whereas thermal vitrification as ex situ technology (Liu et al. 2018b). Although vitrification is proven to be a safe technique in terms of storage or disposal and easy to apply with good efficiency, it is highly expensive and may release poisonous gas during the process (Bradl and Xenidis 2005; Siveris et al. 2019). Another disadvantage is that the vitrified soil may lost its productive capacity for agricultural use (Liu et al. 2018b). Thermal vitrification of fly ash reduces toxicity index of heavy metals (Pei et al. 2020; Ma et al. 2021). A refinery sludge was found to contain no Mg, Ni, and Pb and only some traces of other heavy metals (<1 ppm) after vitrification at 1400 ° C (Ali 2013). In India, high-level radioactive wastes are vitrified and immobilized in alkali borosilicate glass matrices on industrial scale (Raj and Kaushik 2009).

#### 15.3.2.4 Pyrolysis

Pyrolysis is chemical decomposition of organic pollutants into char and ash at relatively low temperature (~500 °C) in anoxic condition (Vidonish et al. 2016). This technology can remediate soil polluted with a wide variety of pollutants such as heavy crude oil, petroleum sludge, tars, etc. (Vidonish et al. 2016; Li et al. 2018; Vidonish et al. 2018). When petroleum-contaminated soil was pyrolyzed at 500 °C for 30 min, extractable TPH and water-soluble organic matter were completely removed (Li et al. 2018). Pyrolytic treatment of crude oil-contaminated soil at 420 °C for 15 min could remove 99.9% TPH and 94.5% PAHs from soil (Song et al. 2019). Pyrolyzed soil had better water holding capacity, seed germination and plant growth than the contaminated soil (Kang et al. 2020). Pyrolytic remediation offers viable and cost-effective remediation techniques for oil-contaminated soil without destroying soil fertility (Li et al. 2018; Song et al. 2019).

#### 15.3.2.5 Hot Air Injection

Hot air injection is generally used to improve the extraction efficiency of SVE to remove SVOCs. In this technique, large volumes of hot air (50–100 °C) are injected with blowers under pressure through network of wells or drains (Hinchee and Smith 1992). Hot air injection effectively removes 95% TPH and reduces remediation time of diesel-contaminated soil compared with conventional SVE (Park et al. 2005).

#### 15.3.2.6 Steam Injection

Steam injection is the remediation of polluted soil in which steam is forced into subsurface soil through injection wells to increase vapour pressure of VOCs and SVOCs and capture them in gaseous phase (FRTR 2012). It derived its use from enhanced oil recovery in heavy oil reservoirs. This technology is most effective for remediation of soil polluted with organic contaminants that have boiling points less than 250 °C (Hinchee and Smith 1992). Efficiency of removal of pollutants is a function of type and concentration of pollutants, soil properties, temperature of the steam, remediation time, etc. Steam enhanced extraction can effectively remediate BTEX- and PAH-contaminated soil (Nunno et al. 1989; Muhibbu-din and Isaac 2021).

#### 15.3.2.7 Smouldering

Smouldering is a slow, self-sustained burning of contaminant that also acts as fuel under unlimited air supply and converting organic contaminants into heat, $CO_2$, and water (Vidonish et al. 2016). Smouldering as a remediation technology has been widely used in the remediation of coal tar dense nonaqueous-phase liquids (NAPL)-contaminated soils, oil drill, and oil sands. Smouldering could remediate more than 99% of crude oil and coal tar in soil contaminated by NAPLs (Pironi et al. 2011; Scholes et al. 2015) Smouldering reduces concentration of TPH from 38,000 mg kg$^{-1}$ to as low as $<0.1$ mg kg$^{-1}$ (Switzer et al. 2009). The drawback of this technology is that incomplete smouldering due to low temperature may emit toxic gases and particulate matters (Rein 2009).

#### 15.3.2.8 Radiofrequency and Microwave Heating

Electromagnetic radiations with frequencies in the range of 300 MHz to 300 GHz and 500 kHz to 500 MHz are known as microwave and radiofrequency, respectively. Radiofrequency heating (RFH) and microwave heating (MWH) involve the conversion of electromagnetic radiations into thermal energy that increase the vapour pressure and mobility of VOCs, thereby improving the extraction when coupled with SVE (Price et al. 1999; Falciglia and Vagliasindi 2016). Although both techniques are comparable, RFH heating is applicable to homogeneously heat larger volumes of soil with larger penetration compared with MWH and is less affected by dryness. RFH reduced perchloroethylene concentration by 99%, and integrated use of RFH with SVE reduces gasoline range organics by 50% (Price et al. 1999). One advantage of coupling RFH with SVE is that it shortens remediation time by 80% when compared to conventional SVE (Huon et al. 2012). Falciglia et al. (2013) used MWH to remediate soils contaminated with diesel and achieve maximum removal efficiency of 95% when moist soil was treated at 1000 W for 60 min. MWH at 1000 W for 10 min with a frequency of 2.45 GHz could remove 70–100% of PAHs (Falciglia and Vagliasindi 2016). It is also effective in decontamination of soils polluted with nitrobenzene, PCBs, and HCB (Falciglia et al. 2013).

#### 15.3.2.9 Electric Resistance Heating (ERH)

Electric current is passed to warm the soil and then boils in situ moisture into steam. The steam thus generated evaporates the VOC contaminants from the subsurface toward the vadose zone where they are recovered by a vapour recovery or multiphase extraction system (Wolf et al. 2009). This technology has several advantages such as uniform heating of soil and does not impair soil physiochemical properties due to low heating temperature and tolerance to subsurface heterogeneities. ERH with latent heat of 75–150 kWh/yd$^3$ provides a reduction of 90–99% 1,4-dioxane concentration under field condition (Oberle et al. 2015). ERH may also be combined with other technologies to optimize and enhance their performance. Coupling ERH with chemical oxidation (2.5 mmol $Na_2S_2O_8$ g$^{-1}$) improves the remediation efficiency of phenanthrene to 79.42% compared with 35.9% by ERH, and the increase in benzo(a)pyrene was from 23.5 to 85.47% when ERH is coupled with oxidant in PAH-contaminated soil (Han et al. 2021b). The overall removal efficiency can also be increased by increasing the voltage. Geng et al. (2021) reported that modification of pulsed direct current to alternating current enhanced trichloroethylene extraction efficiency to more than 90%.

#### 15.3.2.10 Electrokinetic Separation

Electrokinetic separation is an in situ remediation method for soils contaminated with water-soluble contaminants. Low-intensity electric field is applied through a pair of electrode, and contaminants are allowed to migrate through a porous solid medium, especially in low hydraulic conductivity soils. The main transport mechanisms of contaminants are electromigration, electroosmosis, electrophoresis, electrolysis, and diffusion (Wen et al. 2021). The extent of removal is governed by polarity of the contaminants, soil properties, and remediation time (Al-Hamdan and Reddy 2008). Electrokinetic remediation of Hg contaminated soil caused removal of 60% total Hg in 3 months, leaving behind Hg as insoluble salts (45%) and metallic form (55%) (Ferro et al. 2014). It is also an effective technique to remediate Ni and Cd (Sivapullaiah et al. 2015), As (Kim et al. 2012), radioactive substances such as U and Rd. (Miao and Pan 2015; Arias 2020) and organic pollutants (Reddy and Saichek 2004). The efficiency is often enhanced by adding facilitating agents such as surfactants, co-solvents, nanoparticles, oxidizing chemicals, etc. or coupling with other technology (Han et al. 2021a). Although this technology has lesser environmental impacts, high electricity consumption may hinder its application (Virkutyte et al. 2002).

#### 15.3.2.11 Photocatalytic Oxidation

Photocatalytic oxidation is an advanced oxidation process that uses visible or UV light to activate catalysts to oxidize organic pollutants into simple inorganic products, mainly $CO_2$ and $H_2O$. Common photocatalysts include semiconductor such as $TiO_2$, ZnO, $Fe_2O_3$, $MoS_2$, CdS, g-$C_3N_4$, metal-organic ligands framework, etc. The reactive oxygen species produced during photocatalytic reaction is responsible for the degradation of recalcitrant compounds (Ossai et al. 2019). Degradation depends on the type and composition of photocatalyst, light intensity, pH of the medium and oxidizing agents/electron acceptors and is least affected by pollutant concentration and amount of catalyst (Higarashi and Jardim 2002; Ahmed et al. 2011). Heterogeneous photocatalytic treatment using $TiO_2$ combined with solar light was very efficient in the destruction of pesticide Diuron in the top 4 cm of contaminated soil (Higarashi and Jardim 2002). UV light illuminated on $TiO_2$ degrades up to 85% of phenanthrene (Asadi et al. 2007). Solar light irradiated over ZnO efficiently degrade 4-nitrophenol (Rajamanickam and Shanthi 2016). One major advantage is that this technology uses clean and abundant solar energy to catalyse contaminant degradation and does not emit off-gas (Wang and Ray 2000; Xia et al. 2021).

## 15.3.3 Biological Techniques

Bioremediation is a 'greener' remediation approach that relies on living organisms such as plants, microorganisms, etc. to destroy or reduce the hazards of soil pollutants (Glazer and Nikaido 2007). It is a cost-effective, safe and sustainable technology, often combined with other remediation measures. The effectiveness of bioremediation depends on the physicochemical properties of the polluted soil, type and concentration of pollutants, and the organism used for bioremediation (Gallego et al. 2011). The different types of bioremediation techniques are described in this section.

### 15.3.3.1 Phytoremediation

Phytoremediation is an inexpensive, simple and eco-friendly remediation of organic and inorganic pollutants using different plant species (Martin and Ruby 2004; Liu et al. 2018a, b). Different phytoremediation strategies include phytostabilization, phytostimulation, phytotransformation, phytofiltration and phytoextraction (Fig. 15.2).

### 15.3.3.2 Phytostabilization

Phytostabilization or phytoimmobilization is chemical stabilization of heavy metal pollutants by employing plants that can reduce the mobility and bioavailability of heavy metals by its roots (Gerhardt et al. 2017). Various non-organic and/or organic soil amendments such as compost, biosolids, clay minerals and nutrients with suitable plant species may improve phytostabilization (Flathman and Lanza 1998; Wuana and Okieimen 2011). *Miscanthus giganteus* is a potential candidate to phytostabilize Cd and Hg in contaminated soils (Zgorelec et al. 2020). Halloysite as an ammendment aided *Festuca rubra* L. in phytostabilization of Cu in Cu-contaminated soil (Radziemska et al. 2017) and *Brassica juncea* L. in Cr-contaminated soil (Radziemska et al. 2018). One of the advantages of phytostabilization is that it does not require disposal of hazardous plant biomass (Wuana and Okieimen 2011).

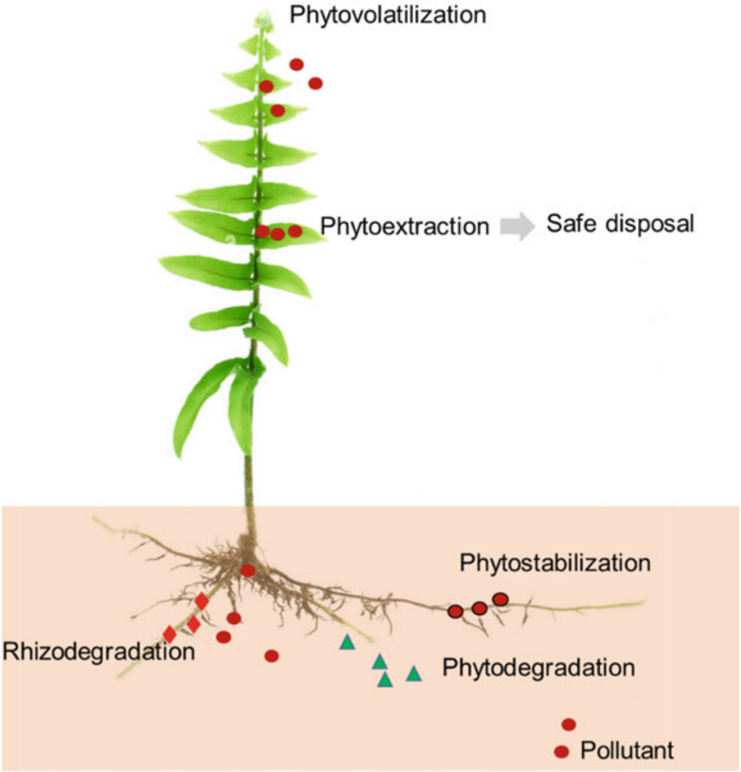

**Fig. 15.2** Phytoremediation strategies

### 15.3.3.3 Phytostimulation

Phytostimulation (rhizodegradation) is enhanced biodegradation of organic pollutants by improving microbial activity in the rhizosphere (Mukhopadhyay and Maiti 2010). Secretion of exudates boosts microbes that degrade pollutants. Root exudate from *Zea mays* stimulates native *Streptomyces* strains capable of degrading organochlorine pesticide lindane (Álvarez et al. 2012). Growing *Pisum sativum* L. (*cv.* Blauwschokker) in soil spiked with biodiesel (50 g kg$^{-1}$) hastens the degradation process (Hawrot-Paw et al. 2019). Biodegradation of imidazolinone herbicide was greater in soils where leguminous crops are grown than in unvegetated soils (Souto et al. 2020).

### 15.3.3.4 Phytodegradation

Phytodegradation (phytotransformation) is a bioremediation technique in which pollutants are taken up by plant roots and metabolized and degraded in plant tissue (Vishnoi and Srivastava 2008; Kumar and Gunasundari 2018). It is a particularly successful technique for remediation of soils contaminated with organic compounds and heavy metals such as Hg and Se (Kumar and Gunasundari 2018). Several plant species have been reported to efficiently degrade several contaminants in the polluted environment. *Helianthus annuus* actively take benzotriazoles in its tissue (Castro et al. 2003). Axenically cultivated *Myriophyllum aquaticum*, *Spirodela oligorrhiza* L. and *Elodea canadensis* have the potential to phytodegrade up to 95% of organophosphorus pesticides (Gao et al. 2000).

#### 15.3.3.5 Phytoextraction (Phytoaccumulation)

It is a bioremediation technique of adopting fast-growing plants or slow-growing plants capable of producing high biomass to accumulate heavy metals to clean up polluted soil. According to Ghosh and Singh (2005), there are three types of strategies to improve phytoextraction, i.e., natural (continuous) phytoextraction, induced or chelate assisted phytoextraction and genetic engineering. Natural phytoextraction is the use of metal-accumulating plants to concentrate metals in the shoots. Yan et al. (2020) presented several promising hyperaccumulators. Maximum concentrations of As, Cd, Co, Cr, Cu, Hg, Mn, Ni, Pb, Se, and Zn are found in *Pteris vittata* (8331 ppm), *Phytolacca americana* (10,700 ppm), *Haumaniastrum robertii* (10,232 ppm), *Pteris vittata* (20,675 ppm), *Eleocharis acicularis* (20,200 ppm), *Achillea millefolium* (18,275 ppm), *Schima superba* (62,412 ppm), *Psychotria douarre* (47,500 ppm), *Medicago sativa* (43,300 ppm), *Lecythis ollaria* (18,200 ppm) and *Thlaspi caerulescens* (51,600 ppm), respectively. Non-hyperaccumulator woody plants (poplar, willow) and crop plants (*Melilotus alba* L., *Trifolium pratense* L., *Malva verticillata* L., *Carthamus tinctorius* L., *Cannabis sativa* L. and *Helianthus annuus*) that produce enormous plant biomass also accumulate heavy metals in their biomass and are efficient phytoextractors (Tlustoš et al. 2006; Herzig et al. 2014; Kacálková et al. 2015). Chelate-assisted phytoextraction uses different chelating agents such as EDTA, DTPA, low-molecular-weight organic acids, etc. to facilitate significant metal accumulation in shoots (Sun et al. 2011). Soil amended with either elemental S or nitrilotriacetate (NTA) increased uptake of Zn, Cd and Cu in non-hyperaccumulator crop plants, thereby increasing its phytoextraction (Kayser et al. 2000). Yan et al. (2017) recommended EDTA and NTA as the most suitable chelating agents to improve phytoextraction of Pb by *Mirabilis jalapa*. Artificial strategy is also adopted to enhance heavy metal accumulation capacity and tolerance of plants through increased levels of binding agents such as phytochelatins and metallothioneins (Cobbett 2000). Although EDTA treatment increased Cd and Zn phytoextraction by *Zea mays*, it was much smaller compared with the natural hyperaccumulator *T. caerulescens* (Lombi et al. 2001). Genetic tools such as gene editing, stacking genes, and transformation may be exploited to develop superior cultivars that can withstand high concentration of pollutants with improved phytoextraction traits. Approaches include transfer of genes from other organisms or its overexpression in the same plant species (Das et al. 2016). In *Brassica juncea* trangenics, overexpression of adenosine triphosphate sulfurylase, γ-glutamylcysteine synthetase and glutathione synthetase gene enhanced Se accumulation than in wild type (Doty 2008). Despite the success of this technology, there is environmental apprehensions related to leaching of heavy metal to groundwater as a result of increased bioavailability and slow process.

#### 15.3.3.6 Disposal of Hyperaccumulators

One major concern associated with phytoextraction is safe disposal of hyperaccumulators that contain high concentration of toxic heavy metals. Various disposal mechanisms include composting, incineration, pyrolysis, compaction, etc. (Cui et al. 2021; Liu and Tran 2021). Cao et al. (2010) use composting to pre-treat As-rich hyperaccumulator *Pteris vittata* L., thereby reducing its biomass as well as As content. Pyrolysis of *Boehmeria nivea* stabilized Cd, Cr, Zn, Cu and Pb in the residue and act as an excellent sorbent of methylene blue (Gong et al. 2019). Incineration technology was used to volatilize As and reduce biomass of hyperaccumulator *Pteris vittata* L. (Yan et al. 2008). Ni was removed from harvested *Odontarrhena chalcidica* cultivated on Ni-rich galvanic sludge providing similar Ni yields as from natural soils (Tognacchini et al. 2020).

#### 15.3.3.7 Limitations of Phytoremediation

Although phytoremediation is a promising remediation technique, it is not without limitations. The success of phytoremediation depends on the growing conditions required by plants. Phytoremediation is limited to shallow soil where there is rhizosphere activity. It is slow process, and remediation time taken for clean-up exceeds other conventional physicochemical and thermal methods. Slow plant growth and low biomass production limit the efficiency. Another issue is that solubility of contaminants might increase with time, increasing risk of leaching and entry to food chain in case of mismanagement (Ali et al. 2013).

#### 15.3.3.8 Bioventing

Bioventing is the introduction of electron donors such as $O_2$ (aerobic bioventing) or $N_2$ (anaerobic bioventing) with atmospheric pressure or blower to unsaturated soils to aid in biodegradation by existing soil microorganisms and is highly efficient for hydrocarbon-contaminated sites (Zimmerman et al. 2003). Oxidative transformation occurs in aerobic bioventing, while reductive transformation occurs in anaerobic bioventing (Hohener and Ponsin 2014). Bioventing of diesel-contaminated soil for 150 days could remediate up to 82.0% of TPH (Lee et al. 2006). Bioventing diesel contaminated soil for 60 days could achieve 85% removal efficiency (Thomé et al. 2014). Bioventing for 7 months could clean up 93% of phenanthrene in an artificially phenanthrene-contaminated soil, resulting in low ecotoxicity (Frutos et al. 2010). Coupling bioventing with SVE enhanced pollutant removal (Amin et al. 2014a, b). The practical application of bioventing is often limited by very low moisture and permeability (Mosa et al. 2016).

#### 15.3.3.9 Bioslurping

Bioslurping is an enhanced multiphase extraction technique that combines bioventing, vacuum-enhanced free product recovery and soil vapor extraction to remediate anoxic sites polluted with light non-aqueous phase liquids (LNAPLs)

(Gidarakos and Aivalioti 2007). The bioslurping system consists of bioslurping wells with a slurp tube lowered into the LNAPL layer and vacuum pump capable of extracting liquids and vapours (Gidarakos and Aivalioti 2007). It nearly eliminates emulsion formation and reduces LNAPLs (Place et al. 2003). It also enhanced the activity of hydrocarbon-degrading bacteria (Caredda et al. 2007). Bioslurping is limited by excess moisture (Philip and Atlas 2005).

### 15.3.3.10 Biosparging

Biosparging is an in situ bioremediation in which air is injected below water table (saturated zone) to cause upward movement of VOCs toward unsaturated zone and stimulate aerobic biodegradation (Hussain et al. 2021). It may be combined with bioventing or SVE to capture the released vapours. Efficacy is limited by low permeability of unsaturated zone, causing poor air distribution and contaminant biodegradability (Philip and Atlas 2005). Biosparging at a petroleum oil spill site showed removal of more than 70% of BTEX in 10 months (Kao et al. 2007). Enhanced biosparging with injection of appropriate substrates and inocula through aerobic-activated sludge significantly improved TCE removal from groundwater (Kuo et al. 2012).

### 15.3.3.11 Biostimulation

Biodegradation by intrinsic microorganism is often limited by nutrients, C availability, pH, temperature, redox, moisture, $O_2$ and characteristics of the pollutants (Bundy et al. 2002). Hydrocarbons have very high content of C compared with N and P, which severely impairs the catabolic activity of indigenous microorganisms (Tyagi et al. 2011a, b). For efficient biodegradation, optimum C/N/P ratio needs to be maintained at around 100:10:1 (Shahi et al. 2016). Addition of rate-limiting nutrients to optimize the C, N and P content improves biostimulation. Kalantary et al. (2014) reported that phenanthrene biodegradation by biostimulation with consortium of adapted microorganisms was optimum with addition of macronutrient and micronutrient in the range of 67–87% and 12–32%, respectively. Biostimulation on hydrocarbon degradation in petroleum-contaminated loessal soil with N and P improved TPH degradation efficiencies 28.3% after 12 weeks of remediation (Wu et al. 2019a, b). Polyurethane waste degradation in soil was improved by 62% when biostimulated with yeast extract alone or with polyurethane dispersion agent impranil (Cosgrove et al. 2009). Biostimulation of petroleum reservoir to improve oil recovery has been conducted in a large number of oilfields (Gao et al. 2013). It also diminishes leaching of contaminants and improves microbial growth, thereby enhancing biodegradation (Simpanen et al. 2016). Biostimulation also accelerates calcite precipitation to immobilized Cu in soil (Chen and Achal 2019).

### 15.3.3.12 Bioaugmentation

Bioaugmentation is the inoculation of contaminated site with efficient exogenous microbial strains or cultures to augment contaminant biodegradation (Xu and Lu 2010). These microorganisms may be isolated from contaminated site or genetically engineered to produce versatile enzymes and bioproducts that aid in biodegradation of contaminants (Adams et al. 2015). *Rhizobium trifolii*, isolated from atrazine-contaminated soil, augment 2,4,6-trinitrotoluene degradation by 60% within 2 days (Labidi et al. 2001). Introduction of microbial consortia of fungi and bacteria to indigenous microbes significantly enhanced PAH degradation by 41.3% in aged polluted soil (Li et al. 2009). Addition of two bacterial strains, *Achromobacter* sp. (ACH01) and *Sphingomonas* sp. (SPH01), isolated from soil polluted by PAH augments PAH degradation and decreases the concentration from 99.5 ppm to 7.9 ppm, efficiently reducing the phytotoxic effect to *Vicia faba* L. (Castiglione et al. 2016). When *P. aeruginosa* is added to soils co-contaminated with heavy metals and hydrocarbons, it promotes plant growth by alleviating plant stress (Agnello et al. 2016). Bioaugmentation is advantageous when indigenous microbial populations are affected by contaminants, and the introduction of exogenous species tolerant to contaminants can immediately start biodegradation (Tyagi et al. 2011a, b). Although success of bioaugmentation has been reported, some studies indicate failure of potential degraders in natural systems while others enhanced degradation efficiencies temporarily (Goldstein et al. 1985; Polyak et al. 2018).

#### 15.3.3.13 Bioattenuation

Bioattenuation or natural attenuation is the use of natural biological processes to degrade, transform, stabilize or immobilize pollutants without enhancing biodegradation activity (FRTR 2012; Abatenh et al. 2017). It is usually applied when contaminant concentrations are low and when time is not a limiting factor and requires constant monitoring. Natural attenuation efficiently degraded more than 99% of fluorene and phenanthrene, and 30% of pyrene in PAHs contaminated mangrove sediments within a month (Yu et al. 2005). A 90-day pot experiment showed that natural attenuation could result in reduction of about 37–57% of TPH (Agnello et al. 2016; Guarino et al. 2017). In a pot study with soil amended with sewage sludge for more than 35 years, Tai et al. (2016) reported that there was little or no natural attenuation and soil still contains high heavy metals, organic matter and nutrients.

#### 15.3.3.14 Landfarming

Land farming is engineered bioremediation system that uses periodic tilling or plowing for better aeration and mixing to enhance biodegradation of organic contaminants (Tomei and Daugulis 2012; Ossai et al. 2019). Mmom and Deekor (2010) reported that land farming efficiently reduced 14.54–82.24% of TPH and 16.01–50.54% of PAH during the remediation of hydrocarbon-polluted sites in the Niger Delta. Biodegradation in land farming can be augmented by addition of microbes, oxygen, moisture and nutrients. Pot study showed that bioaugmentation-assisted land farming for 90 days produced greater reduction of TPH (86%) compared with land farming alone (70%) (Guarino et al. 2017). Large-scale land farming in Niger Delta, Nigeria, contaminated with petroleum hydrocarbons showed that NPK fertilizer amendment resulted in 43% TPH reduction (Brown et al. 2017a, b). A laboratory-scale land farming bioaugmentation through the addition of microbes and nutrients achieves TPH removal efficiency of 70–72%, and the use of post-oxidation treatments with 5% $KMnO_4$ improves the overall efficiency to 92–93% (Bajagain et al. 2020). Addition of soils contaminated with diesel to land farm followed by tillage and irrigation could remove around 64% of diesel in the first year (Johnsen et al. 2021). Land farming through the addition of fertilizer and aeration by rototilling enhanced bioremediation of diesel-contaminated soils in the Arctic (Paudyn et al. 2008). Despite simplicity and relative success in large scale, limitation includes additional cost involved during excavation, low efficiency, and risk of volatilization or leaching of hazardous pollutants (Maila and Cloete 2004; Brown et al. 2017a, b).

#### 15.3.3.15 Composting

Composting in bioremediation refers to the use of microorganisms to sequester or convert organic contaminants to innocuous stabilized by-products by thermophilic microorganisms. The efficiency of this process depends on parameters like balanced C/N ratio, pH, moisture content, particle size and addition of suitable microbial consortia (Prakash et al. 2015; Mihai et al. 2020). Composting of a dehydrated Binyi oil-containing sludge showed that oil content in composting with commercial bacterium and nutrient decreased from 110,160–60,800 mg $kg^{-1}$ in 160 days (De-qing et al. 2007). Composting with horse manure degrades 78–93% of petroleum-based oil wastes with the disappearance of most PAHs except pyrene, chrysene and dibenz(ah)anthracene within 4.5 months of composting (Kirchmann and Ewnetu 1998). Composting coupled with rhizodegradation could reduce TPH from 7900–17,900 to 1400–3700 mg $kg^{-1}$ (Wang et al. 2011).

#### 15.3.3.16 Biopiling

Biopiling (biocells, bioheaps or biomounds) is a remediation technology in which contaminated soil is excavated; treated with bulking agents such as straw, saw dust, etc., nutrients and water; and piled in a heap for biodegradation. Mixing may be done though aeration pipe or special mixing devices (Jorgensen et al. 2000; Li et al. 2004). Biopiling of lubricating oil-contaminated soil with bark chips and nutrients degrades about 70% of the mineral oil within 5 months (Jorgensen et al. 2000). Biopiling of diesel-contaminated soils achieve 70% decontamination in 40 days and reached 85% in 76 days (Chemlal et al. 2012, 2013). During this process, there was synergy between bacteria and fungi in contaminant removal. Biopiling technique removes 58% of TPH, of which 33% was removed during seasonal freezing and early thawing over winter in a cold climate (Kim et al. 2018). Sequential processes of biowashing and biopiling removed 86% TPH in 20 days (Kim et al. 2019). Biopiling with vermicompost enhances recovery, improves soil properties and reduces potential toxicity of Cu, Zn, As, Pb, Cd and Sb (Olivia et al. 2021). Biopiling method is also effective to remediate diesel oil contaminated soil in the sub-Antarctic region (Delille et al. 2008). Optimization of C/N/P ratio, pH, adequate moisture and optimum temperature in biopiling is necessary to improve efficiency of microbial hydrocarbon metabolism (Jorgensen et al. 2000; Siles and Margesin 2018; Zhang et al. 2021).

#### 15.3.3.17 Slurry Phase

Slurry-phase bioremediation is treatment of polluted soil in a bioreactor to enhance aerobic or anaerobic biodegradation. The excavated soil may be crushed and screened for better mixing and homogeneity before loading in the reactor (Tomei and Daugulis 2012). In the bioreactor, the solids are maintained in slurry (10–30% solids by weight) with ideal nutrient concentrations, dissolved $O_2$, pH and temperature (Woodhull and Jerger 1994). If a suitable population is not present, single or mixed microbial consortia is added. When biodegradation is complete, the slurry is pressed through a filter for dewatering (FRTR 2012). Batch slurry phase bioremediation with the addition of molasses as C substrate degrades 97% high melting explosive in 4 months (Boopathy 2001). Improving $O_2$ supply in slurry-phase bioremediation removes around 95% of 2,4,6-trinitrotoluene within 9 days, while the same amount of removal took 15 days without aeration (Sheibani et al. 2011). Microorganisms (*Bacillus cereus*, *B. thuringiensis*, *Geomyces pannorum* and *Geomyces* sp.) isolated from crude oil-contaminated soils removed 88% TPH in slurry phase, which is higher than solid phase (80%) in 30 days (Maddela et al. 2016). A bioreactor treated with *Pseudomonas* sp. and *Bacillus* sp. could achieve 31 and 35% degradation of crude oil-contaminated soil, respectively, whereas a bioreactor that contains both microorganisms had an actual degradation of 36% (Babalola et al. 2021). Although slurry bioreactor shortened bioremediation time, it is labour-intensive and expensive, as it requires excavation and costly slurry reactors (Boopathy 2000).

### 15.3.4 Application of Nanotechnology in Remediation of Polluted Soils

In recent years, nanotechnology has emerged as an invaluable and attractive remediation strategy due to its efficiency and gained lots of attention. Mechanism of contaminant removal includes catalysis, photocatalysis, oxidation, reduction, nanofiltration, adsorption, immobilization, etc. (Qian et al. 2020). Nanoparticles that are being most widely used for soil remediation include nZVI, nanoscale zeolites, metal and metal oxides, C-based nanomaterials and stabilized nanoparticles (Cai et al. 2019; Pan and Xing 2012). Numerous works on the application of nanomaterials in contaminant removal have been reviewed by Bakshi and Abhilash (2019), Qian et al. (2020) and Alazaiza et al. (2021). Nanotechnology is also often combined with other remediation techniques to draw benefits from synergetic interaction of nanotechnology with other remediation strategies. In spite of its success in polluted soil remediation, nanomaterials, as an emerging soil pollutant, may have adverse effects of soil microorganism and ecosystem. However, the ecological ramifications of increasing levels of nanomaterial are not clearly understood (Lewis et al. 2019).

## 15.4 Selection of Remediation Technologies

Several remediation technologies are available for remediation of contaminated site. As a single remediation technique cannot be applied universally to clean up all contaminated site, selecting the best remediation technique is important. This depends on the type of pollutant and extent of pollution, site characteristics, clean-up goals, cost involved and budget, remediation time, acceptance among public and policymakers and any negative impacts associated with it (Liu et al. 2018a, b). For example, bioremediation is unlikely to be successful in soils polluted with high concentration of TPH and metal salt (Almutairi 2019). Critical screening of the most promising or innovative remediation technology could be more time-saving and cost-efficient for practical use, and selection of the best method is a difficult task due to many complexities involved. The best remediation technology is one that reduces the risk from contamination sufficiently without any environmental concern. In most cases, the synergistic interaction between two or more technologies that complement each other is employed to improve contaminant removal. Several tools, such as a screening matrix or decision framework, have been developed over the past decades to select the best available method to restore polluted soil. Tian et al. (2018) reported analytic hierarchy process (AHP) and technique for order preference by similarity to ideal solution (TOPSIS) as the best method for screening best remediation technique for soils contaminated with organochlorine pesticides. Screening with combined AHP and TOPSIS suggested that in situ chemical reduction-oxidation was the best remediation strategy for remediating chromite ore-processing residue site in China (Bai et al. 2015). The Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) provides ranking of the different remediation strategies as well as quantifies the impacts of the different alternatives available (Betrie et al. 2013). Gorsevski et al. (2012) used ordered weighted average (OWA) to evaluate the suitability of a site for use as landfill in Macedonia. Apart from the mentioned tools, many other tools are also available to select remediation methods.

## 15.5 Conclusion

Soil pollution poses significant risk to soil and environmental sustainability and public health. A polluted site remains unusable until remediation measures are taken up to restore some or all of its functions. Although success has been found in the numerous technologies, some have serious secondary problems or may even render the soil uncultivable for future use. All care should be taken during these remediation processes to reduce the secondary ill effects. The best remediation technology is one that can eradicate or reduce the risks connected to contaminated soil. In general, most remediation technologies involve heavy cost and are time-consuming. Therefore, the best approach is to prevent soil pollution.

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# Fertilizer Management in Dryland Cultivation for Stable Crop Yields

# 16

Biswabara Sahu, Bishnuprasad Dash, Satya Narayana Pradhan, Arpita Nalia, and Puja Singh

## Abstract

In India, around 68% of arable land area is dry land, but at the same time, it contributes to 44% of the total national food production. However, extreme weather conditions in such areas lead to soil erosion, moisture depletion, leaching of nutrients, and runoff, leading to scarcity of plant available nutrients. These soils are also low in their carbon content. In this condition, proper fertilizer management is of utmost importance in order to maintain soil health through carbon enrichment, moisture conservation, and regulated nutrient cycling thereby supplying essential nutrients to crops during their critical growth period. Being a potential area for crop production, agricultural practices require more attention on crop management practices in order to meet the food demand of the nation, which also has a significant role in uplifting the socioeconomic condition of the people living in dryland areas.

## Keywords

Biochar · Biofertilizer · Conservation agriculture · Integrated nutrient management

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## 16.1 Introduction

Dry land covers 41% of terrestrial land and 38% of the world's population (Huang et al. 2016; Smith et al. 2019). Challenges associated with dryland ecosystems like land degradation and water scarcity make it the most vulnerable ecosystem (Poulter et al. 2014). The increasing area under dryland and land degradation threatened to negatively impact agricultural productivity and water availability (Nijbroek et al. 2018). As a consequence of land degradation, the organic carbon content of soil declines drastically over time (Pacheco et al. 2018). Reduced soil fertility and unsustainable farming practices result in loss of biodiversity and economy, more so in dry land. In addition to impending land degradation, water scarcity poses a great threat to agricultural productivity in dry land, as the agricultural sector is heavily reliant on sufficient availability of water to produce and sustain maximum yield (Assouline et al. 2015). Fertilizer utility is already below the standard in dryland regions mainly due to inefficiencies of the production-transportation chain in such socioeconomically underdeveloped regions and more to lack of awareness among the growers regarding efficient application of these nutrients.

The increasing food demand of a rising population and reduction in cultivable land and other natural resources are placing unprecedented pressure on current agriculture to meet the world's future food security and enhanced demand for food productivity through sustainable production strategy without having any negative impact on the environment (Foley et al. 2011). Dryland regions are found to be a significant contributor in meeting the food demand of the globe. Like any other agricultural ecosystem, there is inappeasable demand for energy, water, and land for modern societies along with higher crop productivity. The agricultural sector especially through overuse of fertilizer has resulted in nutrient saturation of soil ecosystem causing nutrient losses from field to water bodies through runoff, leaching, immobilization, etc. (Zhang et al. 2012) causing many environmental concerns like eutrophication and GHG emissions (Davidson et al. 2014). There have been studies reporting stagnation or decrease in the yield of the crop in addition to depletion of natural resources and soil health in dryland areas. Further, climate change has magnified the negative impact on the agricultural system. The challenges faced by the dryland system put the rural population at risk of loss of income and food insecurity. Poor agricultural production often left farmers unemployed and forced them to migrate in search of livelihood. Identifying a sustainable management system is the need of the hour, which will prioritize resources conservation and mitigation of environmental impact while aiming for increase in production.

## 16.2 Integrated Nutrient Management Strategy for Nutrient Management in Dryland Agriculture

### 16.2.1 Concept of INM

INM refers to the integration of old and new nutrient management practices into existing farming practices, which is ecologically and economically viable to be adopted by a farmer and that uses all possible sources of nutrients available in an efficient manner. Time and application of nutrients are optimized in such a manner that it synchronizes with crop nutrition demand. INM practices involve the use of organic fertilizer along with inorganic fertilizer, farm waste, crop rotation, cover crop, *Azolla*, green manure, conservation agriculture, deep placement of fertilizer, slow-releasing fertilizer, etc. to maximize crop nutrition.

Integrated application of organic fertilizer with mineral fertilizer enhances crop yield, sustains crop productivity, and increases carbon sequestration (Baishya et al. 2015; Singh Brar et al. 2015), for which INM has been recommended as an alternative practice for sustainable agricultural production (Zhang et al. 2018). Use of FYM, crop residues, green manure, and other sources of organic fertilizer in rice are shown to maintain C level and improve soil health in long term (Baishya et al. 2015; Mandal et al. 2007). The use of organic fertilizer can control the release of nutrients into the soil through mineralization of organic substances to synchronize with crop requirements (Shahid et al. 2013; Yan et al. 2013). Continuous use of chemical fertilizer above crop requirement can result in acidification of soil ecosystem due to release of organic acid; on the contrary, INM showed a rise in soil pH as reported by Baishya et al. (2015). Zhang et al. (2010) and Thakur et al. (2011) noticed that supplementing inorganic fertilizer with an organic source of fertilizer in a rice-based cropping system facilitates the growth of microorganisms, which improve crop productivity due to an increase in organic status of the soil.

Integration of organic fertilizer with mineral fertilizer has been shown to increase the productivity of rice-based cropping system in India as well as all over the world (Babu et al. 2020; Baishya et al. 2017). Further, the long-term experiment conducted over different regions of India (Yadav et al. 2017; Baishya et al. 2015; Nayak et al. 2012) and China (Tong et al. 2014; Liang et al. 2011) confirmed the sustainability of rice-based cropping system under INM.

### 16.2.2 Steps to Formulate INM Strategies

- Determine the nutrient status of soil and nutrient deficiency through visual interpretation or laboratory analysis.
- Assess the constraint of current nutrient management strategies, and interpret it with results of nutrient diagnosis whether the particular nutrient is present in deficient or excessive content.

- Determine nutrient management practices suitable for different climate and soil types. Evaluation of soil nutrient budget helps in the selection of appropriate strategies.
- Assess crop productivity and sustainability of INM strategies.

### 16.2.3 Principles of INM and Improved Fertilizer Management Through INM

The principle of INM is to maximize the biological potential of the crop by managing the rhizosphere to enhance crop productivity. The rhizosphere is a unique environment where plant roots, soil, and microorganism interact, thereby influencing nutrient transformation, supply and concentration, and plant nutrient availability and uptake. Roots adapt some alterations/modifications in their morphology or physiology as a response to changes in nutrient availability in the soil ecosystem. Rather than depending on the excessive application of external fertilizer, rhizosphere management is an effective way to maximize nutrient acquisition and use by crops. Based on the above points, some of the key aspects of INM are:

1. Taking all possible sources of nutrients into consideration to optimize nutrient input: nitrogen input from the atmospheric deposit, irrigation, and indigenous supply is considered as a source of nutrient input.
2. Dynamically matching soil nutrient supply with crop requirement spatially and temporally: usually, farmers tend to apply large quantities of N before planting, as basal, and remaining after 30 days of transplanting (Zhang et al. 2010). This non-scientific application leads to non-synchronization between crop N demand and nutrient supply resulting in loss of N before its acquisition by the plant.
3. Effectively reducing N losses in intensively managed cropping systems: owing to the high solubility of nitrate, the application of excess N fertilizer above crop requirement poses a threat of its loss in the aquatic environment through leaching. Ammonia fertilizers are vulnerable to loss into the atmosphere through volatilization, whereas nitrate fertilizer is at risk of denitrification. INM practices involve the application of N fertilizer in a reduced zone, which can significantly reduce ammonia volatilization and reduce leaching loss. Application of nitrification inhibitor and organic fertilizer is effective in reducing N loss.
4. Giving priority to the application of organic fertilizer: since the green revolution, the application of inorganic fertilizer in crop fields increased multi-fold to cope with the rising food demand and support high-intensity agriculture. In recent years, it is reported that inorganic fertilizer input increased without a corresponding increase in crop yield, which further decreases nutrient use efficiency and has an environmental concern. Therefore, the inclusion of organic fertilizer is necessary for INM practices. Organic fertilizer improves the water holding capacity and physical structure and biological properties of soil and encourages the growth of soil flora and fauna. Organic matter reduces the fixation of P and also acts as a sink for different nutrients, which will otherwise be loosed

from the soil ecosystem. The use of organic fertilizer available locally can save the cost of fertilizer input for farmers.

### 16.2.4 Progress in INM Practices

Garai et al. (2014) reported a significant increase in rice yield and N and P in soil with the inclusion of phosphorus-solubilizing bacteria in INM practices. As suggested by Chander et al. (2013a, b), INM improves uptake of S and Zn and reduces chemical fertilizer by 50% in soybean. Chander et al. (2013a, b) reported a 92% increase in maize yield in INM than conventional farming practices. Rahman et al. (2013) reported that the application of mungbean/sesbania residue increased productivity in a maize-legume-rice cropping system.

Meena et al. (2019) conducted a long-term study on the effect of the maize-chickpea cropping system to evaluate integrated nutrient management on crop productivity and soil health. The results showed that the application of 75% NPK along with organic manure (FYM and poultry manure) significantly increases crop productivity and soil health. Increased productivity with organic manure application could be attributed to improved nutrient acquisition and utilization from the soil. Besides, the application of organic also improves the population of soil microorganisms. Higher biomass recorded in chickpea could be due to an improved biological environment, leading to better root growth and higher nutrient absorption. Further, combined use of STCR-based 75% NPK and FYM (5 Mg ha$^{-1}$) recorded the highest sustainable yield index (SYI). Further, the highest soil organic carbon content with a high FYM plot indicates that combined use of inorganic and organic fertilizer is essential to achieve a maximum yield throughout as well as maintaining or improving soil quality.

## 16.3 Nutrient Management Through Principles of Conservation Agriculture

The main constraint of dryland areas is scanty rainfall and high evaporation loss due to high temperature of the region. These constraints result into many secondary adverse situations like moisture deficiency, surface salinity, or degraded soil structure, all of which lead to losses in crop production. Such constraints also play a major role in degrading habitat of soil microorganisms, thereby affecting their natural activity negatively. The lower productivity of dryland areas mostly occurs owing to the lower nutrient use efficiency (NUE) (Saleem et al. 1996) of such areas, which causes a 20–25% loss in NUE according to Rashid et al. (2004). Loss of crop nutrients from soil in dry lands is mainly due to leaching loss, rainwater seepage, extreme weather events, runoff in rainy season, soil erosion leading to degraded soil condition, low soil profile moisture during critical crop growth stage (FAO 1981), and lower water holding capacity of the soils. Along with the above problems, a major issue of the dryland region of central Asia is increased salinity due to higher water table and higher evaporation, which can be checked by management practices that require excessive water to stop surface salt accumulation or even water to wash out the excessive surface salt buildup (Devkota et al. 2013). Saving profile moisture in regions where moisture is already scanty can be achieved through adoption of CA principles. Conserving the soil moisture is a feasible way to check surface accumulation of soluble salts and improve the soil quality as well as water and nutrient use efficiency (Humphreys et al. 2010; Singh et al. 2008; Timsina and Connor 2001).

The first and foremost principle of improving nutrient use efficiency of dryland region through conservation agriculture is by making efficient use of moisture conservation because scarcity of water hinders nutrient supply to the roots though the nutrient is present in abundant amount in the profile. For example, direct seeded bed method of rice could save 19% more irrigation water, and by default this method required only 30% of the water applied through traditional paddy rice method; along with that, percolation and seepage loss was approximately 90% less in direct seeded rice with almost double rate of infiltration as compared to control plots (Devkota et al. 2015). Even under water scarce condition, decomposition and mineralization of organic matter are quite slow to meet the nutrient demand of the crop during the crop growing season, while mineralization of organic N is proportional to the amount of water present in the soil within optimal temperature range (Li et al. 2009b).

CA has multifaceted benefits along with conserving soil moisture through residue addition, checking runoff and leaching losses, reducing evaporative loss by acting as a barrier to the exposed sunrays, and restricting erosion losses by promoting soil structure formation and its stability (Findeling et al. 2003; Tarkalson et al. 2006; Adekalu et al. 2007), soil organic carbon builds up. The main reason for loss of nitrogen from soil profile is via leaching loss and volatilization loss at high temperatures, both of which are prevalent in dryland regions. But through CA adoption, these two pathways of nitrogen losses can be hindered.

Not only through soil nutrient buildup, a healthy plant stand supported through better seed, fertilizer placement (Jat et al. 2011), weed control (Zhang et al. 2010), and pest life cycle chain breakage through crop rotation can improve agronomic use efficiency of crops with higher productivity. Nutrient withdrawal through growing crops is higher than nutrient supplied to them in dryland areas, resulting in negative imbalance of major plant nutrients present in soil profile (Irshad et al. 2007; Murage et al. 2000). The basic concept behind nutrient management through CA, which is “feed the soil, and let the soil feed the plant,” is beneficial in building soil nutrient status as well as regulating soil health and ecosystem functionality of dryland soils.

### 16.3.1 Nutrient Management in Dryland Regions Through Each Principle of CA

Each principle of CA has a role in nutrient supply to plants either directly through addition of residues, which on decomposition act as source of nutrient to the standing crops, or by restricting leaching loss and improving nutrient retention in the root zones or by building nutrient repository in soil especially in top soil (Scopel et al.

**Table 16.1** Contribution of principles of CA toward nutrient enrichment and nutrient cycling in soil profile

| Minimum soil disturbance | Permanent organic cover | Crop rotation (legume in rotation) |
|---|---|---|
| Optimum aeration in rooting zone<br>Water movement, retention at rooting depth and release at the time of need<br>Moderate organic matter oxidation, thus supplying nutrients for a prolonged period of time | Buffering against severe impact of solar radiation and rainfall thus no hindrance to nutrient cycling<br>Raised cation-exchange capacity for nutrient capture, retention, and slow-release<br>Adequate substrate for soil organisms' activity, which promotes nutrient supply and complex formations | Biological N-fixation in appropriate conditions, limiting external costs<br>Prolonged slow-release of such N from complex organic molecules derived from soil organisms<br>Soil improvement by organic-matter addition at all depths due to varying rooting patterns of crops grown<br>Healthy plant stands due to disruption of pest cycle |

2004; Erenstein 2002), though the added organics affect nutrient enrichment in soil profile (Kassam and Friedrich 2009, Table 16.1).

Judicial use of natural resources and chemical fertilizers can be beneficial in reducing the losses caused due to leaching, soil erosion, nutrient mining, etc. and bridge the gap between crop requirement and nutrient status of soil. CA has significant effect on N nutrition of crops in dryland regions with duration of adoption and stubble load. Stubble addition results in immobilization of nitrogen in early growing season (Verhulst et al. 2010), but this is a phase where opportunity for nitrogen loss thought leaching, denitrification, and volatilization is reduced (Follett and Schimel 1989; Rice et al. 1986). Thus, with higher stubble load, a higher rate of nitrogen application is essential (Mason 1992) in the initial years in order to withstand the nitrogen depression period, which can be overcome in the later periods after decomposition of the added residue and mineralization of nitrogen take place owing to microbial activity and residue cycling (Carpenter-Boggs et al. 2003). As per a study conducted by Angus and Grace (2017), wheat stubble constitutes of 1/3 of the applied fertilizer to the crop and keeping the residue in file will return back the nutrient foraged by the plant but during the crop growing period. Similarly, residue addition increases phosphorus availability and efficiency (Sanchez et al. 1997), owing to its higher availability because of presence of organic molecules, which bind to the active sites of clay particles and restrict its affinity toward mineral phosphorus to prevent P sorption (Bhatti et al. 1998). But again, the effect of residue addition is very much climate specific because in regions of heavy rainfall without proper drainage facility, such retention can cause rotting of seeds, weed infestation, and anaerobic condition due to stagnation of water. Residue addition maintains soil moisture, and temperature regime thus optimize the microbial activity, which improves the nutrient use efficiency (NUE). The fertilizer use efficiency of crops can also be improved as residue retention successfully supplies nutrient to the plants during the critical growth stage.

**Table 16.2** Beneficial effect of leguminous crop in rotation

| | |
|---|---|
| Legume in crop rotation | It adds to 40–80 kg N/ha and can improve fertilizer use efficiency of the cool season crops or rabi crops |
| | Disease cycle in the field can be broken due to crops of different nature in sequence (Rowland et al. 1988) |
| | Forage legume in rotation helps build up nitrogen-rich organic matter in soil |
| | It increases total, mineralizable, labile, and biomass nitrogen in soil (Ryan et al. 2008) |
| | Legume provides soil cover that checks soil and nutrient loss |
| | Green manure and leguminous crop residues can improve nutrient use efficiency |

CA atmosphere promotes root proliferation through better soil structure formation and sufficient moisture supply through profile moisture saving. This principle also promotes surface accumulation of phosphorus thus enhancing root length, root volume, and root surface area. The above criteria along with reduced root diameter or a greater number of finer roots, lateral root growth, higher nutrient affinity, higher root threshold value toward nutrient acquisition, more rhizodeposition, and organic root exudation are studied to be the essential root characteristics for improving NUE (Marschner 1995; Fageria et al. 2008). A better root architecture supported through moisture and improved soil structure is beneficial for foraging nutrients by plants, while the organic matter builds up through combined activity of plant root biomass, added residues and elevated microbial activity support NUE and water use efficiency (Franzluebbers 2002) because higher root proliferation ad rooting depth into varying soil profiles restrict nutrient loss at the same time can absorb nutrients from deep inside soil and recycle nutrients in surface profile, which are leached from the top itself (FAO 2001), on which microbial action can bring in the concept of nutrient availability to next-generation crops. Root proliferation and branching give rise to a greater number of longer lasting roots, which act as supportive structures in case of moisture deficit phase and withstand the evaporative losses (Brunner et al. 2015). A higher amount of root-to-shoot ratio is also observed under such water deficit condition (Prieto et al. 2012). There have been many evidences of higher number of mycorrhiza and glomalin formation under CA atmosphere (Borie et al. 2006), which support phosphorus absorption as well as optimum moisture and aeration due to higher amount of stable micro- and macroaggregate formation.

Another important principle of CA is crop diversification. Legume in crop rotation is a highly widely accepted principle of CA with added benefits to the soil. Inclusion of leguminous crop in rotation has benefit of meeting the nitrogen demand of crops because of its ability to perform biological nitrogen fixation. The beneficial effect of leguminous crops for crops is given in Table 16.2.

Use of nitrogen-fixing twigs can be beneficial as the nitrogen recovered from urea and nitrogen-fixing twigs constitute equal half of the total nitrogen recovered in a crop plant (Sharma et al. 2002). The surface-accumulated nitrogen through leguminous roots is generally lost due to soil erosion, but permanent organic mulch along with legume in rotation protects the added organic matter and nitrogen in soil profile.

Again, a protective environment and substrate availability through organic mulch support microbial population and activity. Mineralization of organic matter acts as a double-sided sword as it also promotes organic matter polymerization, aggregate formation, as well as breakdown of raw material and makes available nutrients for plant uptake.

## 16.4 Use of Biofertilizer in Dry Lands as Viable Option for Source of Nutrient to Plants

Indiscriminate use of agrochemicals, particularly fertilizers along with negligence of manure application during post-green revolution era, led to imbalanced nutrition, which declined the yield potential of crops. This imbalanced fertilization not only deteriorates soil quality but also threatens the environmental quality as well as human health. Hence, nowadays, efforts have been channelized toward sustainable production of nutrient-rich quality foods, taking biosafety into consideration. The exploitation of beneficial microbes as a biofertilizer has become the main bioweapon in agricultural sector because of their potentiality in sustainable crop production and food safety. The use of biofertilizers is a promising technology for future farming in view of excess loss of nitrogen and rapid decline in phosphorus stocks.

Rhizospheric soil is a potential source of several microbial taxa, which play a vital role in plant growth though their interference in different nutrient cycling. Various microbial taxa are used as biofertilizers based on their efficacy in nutrient mining, nitrogen fixation, improving water uptake, and disease suppression. Biofertilizers are generally the living microbial inoculants of bacterial, algal, and fungal origin. Biofertilizers make nutrient-rich soil environment through their active involvement in nitrogen fixation; solubilization or mineralization of phosphate and potassium; production of antibiotics and plant growth-regulating substances, i.e., hormones, vitamins, etc.; and biodegradation of organic matter in the soil. Biofertilizers upon application either as seed or soil inoculant undergo multiplication and participate in biochemical cycling of soil nutrients and enhance productivity of the crops. In general, about 10–40% of applied fertilizer is efficiently utilized by the crops, causing a huge loss of chemical ingredients to environment. In this regard, biofertilizers have tremendous importance in modern agriculture in sustaining environmental quality along with enhancing crop productivity to meet the growing demands. The microbial community beneficial for agriculture include N-fixing cyanobacteria, plant growth-promoting rhizobacteria, mycorrhizal association, pathogen-suppressive useful bacteria, and biodegrading microbes. *Rhizobium*, *Azotobacter*, *Azospirillum*, cyanobacteria, *Phosphobacteria*, and mycorrhizae are some of the important biofertilizers in the field of agriculture.

*Rhizobium* plays a crucial role in maintaining nitrogen economy in soil through N fixation in association with legume roots. *Rhizobium* inoculants are reported to increase significantly the gran yield of pulse crops. *Azotobacter* also plays a vital role in nitrogen cycling. Apart from nitrogen fixation, *Azotobacter* also supports plant growth through production of some vitamins like thiamine and plant hormones like cytokinin, gibberellins, and indole acetic acid. *Azotobacter chroococcum* accelerates plant growth through improving root architecture and enhancing seed germination. *Azotobacter* is best suitable for cereal crops like rice, wheat, barley, oat, maize, etc. *Azospirillum* is a free-living aerobic bacterium, which can thrive in flooded condition. *Azospirillum* inoculation leads to change in root architecture through siderophore production, and it also increases surface area of roots, which provides site for sufficient nutrient and water absorption. Blue-green algae are also of great importance because of nitrogen fixation in association with rice crops. *Pseudomonas*, *Bacillus*, *Fusarium*, *Sclerotium*, *Aspergillus*, and *Penicillium* were reported to be active in the solubilization of phosphorous and potassium. *Aspergillus niger* has been reported to facilitate P solubilization through production of phosphatase enzyme and organic acids. Similarly, *Bacillus* and *Clostridium* are observed to be more efficient in K solubilization (Ambrosini et al. 2012). Mycorrhizal association also facilitates plant growth through modifying root geometry, satisfying crop nutrient demands, and protection from pathogen attack. Genetically engineered *Anabaena* sp. having increased potential of N fixation are also used in paddy field, which enhances the activity of nitrogenase enzyme.

Recent meta-analysis on investigating the beneficial effect of biofertilizers in terms of increase in yield and nutrient use efficiency of nitrogen and phosphorus revealed the superiority of effect of biofertilizer under dry climate over other climatic conditions (Schütz et al. 2018). It also showed greater success of arbuscular mycorrhizal fungi inoculation in soils with low organic matter. The seasonal fluctuation in microbial community is less under dry climates. Soil phosphorous is also low in dry lands due to poor diffusion caused by moisture deficit (Syers et al. 2008). Hence, the strong effect of biofertilizer in P solubilization is clearly visualized under dryland scenario. Dry lands cause more evapotranspiration from plant and soil because of hot climate. Application of biofertilizers like *Azospirillum* is beneficial for such region because it may release phytohormones like auxin that results in root elongation thereby facilitating water absorption by plants from deeper soil layers (Steenhoudt and Vandereyden 2000). Similarly, *Azotobacter* is also suitable for dryland regions, which may release hormones like cytokinin and gibberellin that reduces plant stress and enhances crop yield (Bhardwaj et al. 2014). Salinization and drought limit the plant growth in dryland areas. The bacteria (*Bacillus*, *Pseudomonas* sp., etc.) producing ACC deaminase are able to degrade ethylene, which is produced by plants under stress conditions, thus allowing plants to grow well under drought situation (Shaharoona et al. 2007). *Pseudomonas fluorescens* has been reported to produce osmolytes and salt stress-induced proteins, which overcome the adverse effect of salinization (Paul and Nair 2008). *Bacillus polymyxa* is also observed to provide tolerance to salt and heat stress. Conjoint application of arbuscular mycorrhizal fungi along with nitrogen fixing bacteria helped legume crops to overcome drought stress (Aliasgharzad et al. 2006). Arbuscular mycorrhiza inoculation was observed to improve photosynthetic efficiency of rice plant under drought stress (Ruiz-Sanchez et al. 2010). Beneficial effect of mycorrhiza is also reported under salt stress condition. Nowadays, environmental stress is the major driven force behind unprecedented decline in crop productivity. Under these circumstances, biofertilizers are helpful for feeding the growing demand as well as sustaining healthy environment.

## 16.5 Use of Biochar for Nutrient Management in Dryland Areas

Rapid urbanization and growing population have created pressure on farming sector, which adversely affected the soil quality, leading to environmental degradation. Indiscriminate use of fertilizers and pesticides led to environmental pollution like eutrophication, GHG emission, etc. Hence, biochar may be one of the alternatives to improve soil fertility as well as to curb GHG emission under changing climate scenario. Biochar is a pyrolysis product of crop residues, manures, and agricultural wastes under limited oxygen condition. Biochar is one of the important soil conditioners, which improves crop yield and soil health as well as address climate change. Type of raw materials used, duration of pyrolysis, and temperature of pyrolysis are important factors for determining the quality of biochar.

Biochar may play a vital role in dryland agriculture by governing nutrient and water holding capacity of soil. Biochar application facilitates development of soil structure through decreasing bulk density and improving porosity of soil. This enhances heat, water, and gas transport in soil. Factors like rate of application of biochar, shape and porous structure of biochar, particle size distribution of amended soil, and adsorption property of biochar determine porosity, water retention, hydraulic conductivity, etc. Water retention capacity of biochar depends on its internal porosity. Well-oxidized biochar was observed to retain more water than fresh biochar because of increase in oxygen functional group on the surface of biochar. It is also reported that biochar application increases water holding capacity more in sandy coarse-textured soil than clay soil. Biochar also plays a vital role in saline environment. Application of acidic biochar amendments to saline soils of dry land can mitigate salt stress and improve plant growth (Hagner et al. 2016). The mechanism behind reclamation of saline-sodic soils of dry lands is high adsorption capacity of biochar, which offsets the excess $Na^+$ ions, thereby reducing salt stress. Application of biochar also improves CEC of soil with increased buffering capacity. Increased CEC from biochar application results in more nutrient retention on biochar surface, thereby reducing leaching loss of nutrients and enhancing nutrient availability for plants under dryland situations. Application of biochar leads to increase in soil organic carbon, which also facilitates stabilization of carbon in soil through improved soil aggregation and thereby accelerates carbon sequestration and mitigate GHG emission (Azeem et al. 2019). Biochar also provides better niche for soil microbial activity. Biochar application enriches soil organic carbon, which provides substrate for microbial activity. A meta-analysis study indicates that biochar application improves crop yield and limits nutrient leaching, thereby reducing fertilizer requirement and promoting water uptake in less fertile soils of dry arid region (Biederman and Harpole 2013).

## 16.6 Time and Place of Nutrient Application in Dryland Areas

Fertilizer application should be done in a very sensible manner in dryland areas, taking care of the right time, right source, right place, and right method of fertilizer application (Ryan and Sommer 2010). In dryland areas, fertilizer application based on soil test values and placement of fertilizers near root zone can increase fertilizer use efficiency by reducing its substantial losses. Nitrogen fertilizer management should be done very carefully in dryland conditions to get maximum yield of the crops. It is beneficial to apply nitrogen as basal dose in dry conditions, and split application can be done if more rainfall is there. Phosphorus and organic matter are also applied initially. Fertilizer application method varies according to the crop type and soil moisture condition. Split application of nitrogen increases N use efficiency (Uyovbisere and Lombin 1991) and is found to be beneficial for sorghum, pearl millet, maize, and upland rice in dryland areas of India (Spratt and Chowdhury 1978; Kanwar and Rego 1983). Deep placement of nitrogen is better than surface application in dry conditions as more moisture is present in deeper soil layer and more plant roots are also there to utilize those applied fertilizers, which enhances fertilizer use efficiency (Li et al. 2009a). Many scientists have found that deep placement of nitrogen has increased plant uptake and use efficiency by simultaneously reducing volatilization losses of nitrogen (Lu and Li 1987; Rees et al. 1997; Li et al. 1976). Deep fertilization improves crop yield particularly in water scarcity condition. Randhawa and Singh (1983) have found that sorghum crop yields more if N and P are applied by drilling method than at the side of the furrows. Foliar application of nitrogen is a better option where normal soil application is not possible as farmers apply fertilizer depending on the rainfall. Thirty-one percent yield increase has been found due to foliar urea application in dryland wheat crop (FAO 1988). In dryland situations, urea should be applied by mixing it with the soil to avoid volatilization losses (Abdel Monem et al. 2010). Fertilizer use efficiency can be increased by following appropriate fertilizer placement technique and correct timing of application. Band application of ammoniacal fertilizer restricted nitrification, hence reducing leaching losses. Top dressing at important crop growth stages increases the yield as well as quality of the crops. Slow-release or controlled-release fertilizers are beneficial in two ways by supplying nutrients and their uptake by the plant in a synchronized manner. The sustained release of fertilizer nutrients in controlled-release fertilizer not only increases the nutrient use efficiency but also reduces the losses through volatilization and leaching. Use of slow-release or controlled-release fertilizers contributes toward sustainable crop production and also reduces energy consumption and environmental pollution (Liu and Shi 2013). In calcareous soil, band placement of P is recommended to avoid fixation (Ryan and Sommer 2010). In dryland conditions, surface application of phosphorus should be avoided as it is prone to fixation in this situation. Phosphorus should be applied by placing it near the roots of the seedlings, as root proliferation is difficult in dry soil. In severely phosphorus-deficient soil, the seeds of cereals can be sown by mixing with phosphatic fertilizer, which can’t be done in case of N and K, as they delay the germination and increase seedling mortality (Mason 1971). Higher yield of black gram was obtained when the seed is applied by mixing with phosphatic fertilizer or band placement of P fertilizer. Band placement of K nearby the seeds is beneficial. The crop productivity of dryland soil can be increased by amending the soil with essential micronutrients. Applying fertilizers below the soil surface not only enhances fertilizer use efficiency but also efficiently utilizes the soil moisture. Drilling of fertilizers below the soil surface is recommended for dryland areas in India. Fertilizer placement method increased the yield from 340 kg grain to 1500 kg grain per ha$^{-1}$ in dryland areas of India (Venkateswarlu 1987).

## 16.7 Conclusion

Dry lands, offering potential for food production, are completely dependent on vagaries of precipitation. Climate change is a major driving force behind expansion of acreage of global dry lands. Decline in crop yield is a major concern in dryland areas due to the moisture deficit resulting from low, uneven, and erratic rainfall along with high potential evapotranspiration. Late onset of monsoon leading to delayed sowing of crops results in poor yields. Along with precipitation, there is also a great variation in temperature in dry lands. This high temperature along with moisture deficit is the major cause behind the poor organic carbon status of the soil. Dryland soils are also deficient in macronutrients like nitrogen, phosphorous, etc. owing to its proneness to soil erosion. Thus, soils of dry lands are hungry as well as thirsty. High evapotranspiration under moisture stress condition also creates some secondary consequences like soil salinization and drought. Hence, soil moisture conservation plays a vital role in sustaining crop yield in dryland farming.

To have better adaptability along with improved NUE, the management practices should be more flexible following the need of the farmer and local environmental conditions. Integrated nutrient management techniques involving organic manures, compost, green manure, and biofertilizers like *Rhizobium*, *Azotobacter*, *Azospirillum*, BGA, and VAM fungi along with incorporation of crop residues can be an effective strategy toward obtaining sustainable yield improvement in dryland conditions. As INM is a more labor-intensive process and requires mechanization, in order to benefit small-scale farmers, development of more appropriate locally produced and refined mechanization is essential for the wider adaptability of INM in the targeted region. Further, inclusion of legume crops in the cropping sequence or intercropping with cereal crops can play a pivotal role in sustaining the long-term productivity of dryland soils. Mulching of the soil surface along with growing of cover crops can enhance nutrient mobilization and decrease nutrient loss along with runoff water by improving the infiltration rate through increasing the opportunity time while decreasing evaporative depletion and runoff loss. Use of nitrification inhibitors, controlled- and slow-release nitrogenous fertilizers, enhances the nutrient use efficiency in dryland situations. Even both biofertilizers and biochar may be considered as the best alternatives to traditional chemical fertilizers so far. Soil and environmental quality is considered under dryland ecosystem. The constraints to food production in dry lands are making agriculture distasteful as a source of income. So, there is a dire need for the development of a decision support system to evaluate the precise requirement of fertilization and irrigation and to make judicious use of nutrient sources both from organic and inorganic sources for crop nutrition management in dryland areas.

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# Development of a Successful Integrated Farming System Model for Livelihood Sustenance of Dryland Farmers

# 17

L. R. Meena, Lalit Kumar, S. R. Meena, and Anjali

## Abstract

In India, there is no scope left for horizontal expansion of food production due to the scarcity of land. Over the last 40 years (1971–2011), numbers of small holdings are increasing continuously with a rate of more than 2% annually, while the area under operation has only increased by 0.1%; hence, the average farm size has gone down. Small farm holders in India revealed to possess poor access to land, water, inputs, and credit besides technology and market facilities; therefore, sustaining household food security would always remain the key issue for such farmers. To intact with traditional agricultural systems is also not feasible because the increasing need of huge population could not be fulfilled even if we fallow intensive agriculture approaches with heavy input cost. Hence, it has become inevitable to modernize our agriculture by incorporating innovative agricultural techniques based on the appropriate integration of farming system approaches. It has been seen that appropriate integration of distinct component of farming systems, viz., varied types of plants, animals, birds, fish, and other aquatic flora and fauna, and simultaneously increasing opportunities for market integration proved to be viable approaches to ensure higher productivity and profitability by utilizing less space and time. The various farming system components are combined in such a proportion that each component helps each

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other, for example, the waste obtained from one component can be recycled and utilized as a resource for the other via integration. Since, integrated farming is an effective approach in that a judicious mix of one or more enterprises with cropping system is being adopted to harness complementary benefits via effective recycling of farm wastes/residues and also utilizing them as an additional source of income by small and marginal farmers, therefore, it can be a logical tool for long-term sustainability of small and marginal farmers besides providing them more employment. It has also been seen that the production of fish, milk, food grains, vegetables, fruits, mushroom, etc. within the farm has not only helped in improving the standard of living but also provided better nourishment to the farm family members. Different kinds of models/modules, viz., small-scale farming, dryland farming systems, landless farmers, etc., have been developed for distinct farming systems of various areas of India. Further, proper farm mechanization on such farms was not only found to curtail the cost of cultivation by 20–25% but also increase production by 20%.

**Keywords**

Food security · Integrated farming · Livelihoods · Resource integration · Sustainable livelihood · Small and marginal householders · Sustainable agriculture · Value chain

## 17.1 Introduction and Background

As per the tenth Agriculture Census held during 2015–2016, in India, approximately 87% of farmers occupy a landholding of less than 2 hectares per farm family and nearly 47.3% of cropped area of total cropped area of India; hence, this lot, of huge number of farm families, comes under the categories of small and marginal farmers. FAO (Food and Agriculture Organization) in its survey also estimated around 85% of farm families in India as marginal farmers (FAO STAT 2013). As per GoI current estimates, the current average landholding size in India has continuously been declining, and over 87% of operational holdings are below 1.08 ha. (GoI 2015, Table 17.1). The landholdings of small farm families lie between 1 and 2 hectares, whereas the marginal farm families' occupy less than 1 ha land. The landholdings are further shrinking due to rapid industrialization and urbanization as well as family divisions, land ceiling acts, and, in some cases, family disputes. Thus, there is no

**Table 17.1** The distribution of operational holdings in India over the years (2001–2011)

| Landholding size (ha) | 2001 | 2011 |
|---|---|---|
| Holdings <1 ha | >62% (>77 million) | >67% (>90 million) |
| Holdings <2 ha | >80% (>100 million) | >85%(>115 million) |
| Holdings >4 ha | >7% ((> five million) | > 5% (>seven million) |
| Area on farms <2 ha | >35% of net cropped area | >44% of net cropped area |
| Area on farms <4 ha | >39% of net cropped area | >68% of net cropped area |

scope left for increasing the farm size; hence, vertical expansion is seems to be the only way to enhance farm production and doubling the farmer's income in India. As the cropped area is stagnant throughout the world and the population is increasing at a very fast speed, to feed the galloping population, there is immense need to increase the productivity of per unit area. As per a valid estimate of the United Nations done in the year 2013, the human population will surpass 9 billion by the end of 2050; therefore, to meet the diverse dietary needs of world huge population, food production should be more than doubled globally and tripled in developing countries (Mazoyer and Roudart 2006). Hence, to keep pace with the growing trend of population, a proportional increase in food grain production on limited available resources is a must. In developing countries like India, focus should be to enhance the productivity of each and every agricultural component to fulfill the basic needs of households, i.e., food that includes cereals, pulses, oil seeds, milk, fruit, honey, fish, meat, etc., feed and fodder for animals, and fuel and fiber for other needs. But unfortunately, in contrary to that, Indian agriculture has been characterized to manifest slow growth, pegging an unbridled economic growth in the advent of the new millennium. This present-day agriculture situation also remained a matter of deep concern among the planners since the livelihood of more than 65% of the country's population is at stake, those are wholly dependent on agriculture; moreover, the prevailing situation of present-day agriculture is also linked to create imbalance in growth of farming community, which on turn creates inequity in the country. Therefore, keeping in view of all these facts, the National Commission on Farmers aptly addressed the threat to livelihood security and, as a solution, has recommended integrated farming system as one of the effective tools that ensure profitability, balanced food, a clean environment, employment guaranty, and regular income to the farmers throughout the year besides maintaining a high input-output ratio, sustainability which ultimately caused a total upliftment of the rural masses. Thus, sustainable integrated farming systems (SIFS) approach, if adopted properly, could be a reliable way out to increase farm productivity manyfold because the approach not only accommodates a high level of diversification and resource integration and creating market linkages but also recognized a dynamic approach that can be applied to any farming system around the world. Though to enhance the productivity of different agricultural components exhaustive efforts have been made in the direction of farming systems approaches, still, desired results could not be achieved due to lack in proper integration of different components of the farming system. Since there is no scope of horizontal expansion of food production owing to declining land availability (Anderson and Genicot 2015), appropriate integration of distinct component of farming system by including the increased opportunities for market integration would certainly be a viable approach to ensure higher productivity by using less space and time and can also operate a logical tool for long-term sustainability of small and marginal farmers. Due to prevailing traditional agricultural systems are also not feasible because the increasing need of huge population could not be fulfilled even if we fallow intensive agriculture approaches by involves heavy input cost. Hence, it has become inevitable to modernize our agriculture by incorporating innovative agricultural techniques based on the appropriate integration of farming system approaches. Integrated farming is a system that tries to imitate nature's principle; it does not only incorporate crops but also includes varied types of plants, animals, birds, fish, and other aquatic flora and fauna to maximize farm productivity and profitability. The various components as explained above are combined in such a proportion that each component of farm helps each other, for example, the waste obtained from one component can be recycled and utilized as a resource for the other via integration. Sustainable management of resources in small farms can effectively be achieved by following the appropriate practice of integrated farming system where species diversification and resource integration contribute to regaining productivity. Since integrated farming system includes various farm components at one place, which makes the system a labor-intensive one, thereby, the system can be efficient enough to engage the farmer family effectively throughout the year on their farms. Development of several outlets for selling of the farm produces at the farm level is also essential for appropriate integration of the components as well as to avail of the benefits of resources. However, integration of various components on their farms in absence of a single source/scheme that provides support on various aspects is a big challenge for small farmers. It was seen that the production of fish, milk, food grains, vegetables, fruit, mushroom, etc. within the farm has not only helped in improving the standard of living but also provided better nourishment to the farm family members. A farming system also implies a set of interrelated practices and processes organized into a functional entity; it involves the individual component effect as well as interaction effect while transforming inputs into outputs. In other words, integrated farming is a kind of resource management strategy to achieve "6 Fs," viz., food, feed, fodder, fuel, fiber, and fat, which are not only essential commodities of a household but also incarnate a small farm to generate additional profit as well to make it environment-friendly and sustainable.

An integrated farming system also takes into account the components of soil, water, crop, livestock, and other sources by keeping the farm family at the center for managing agricultural and related activities and even on-farm activities. Thus, in true sense, integrated farming system is an appropriate combination of farm enterprises such as crops, livestock, fishery, forestry, poultry, sericulture, mushroom farming, etc. vis-a-vis to arose other means available to the farmers for profitability. An appropriate integrated farming system interacts adequately with the environment without disturbing the ecological and socioeconomic balance on one hand and attempts to meet out the national goals on the other (Gill et al. 2009). Since integrated farming is an effective approach in that judicious mix of one or more enterprises with cropping system being adopted to harness complementary benefits via effective recycling of farm wastes/residues and also utilizing them as an additional source of income by small and marginal farmers, hence, this kind of farming system arrangement offers us an opportunity to utilize the waste of one component as input, leaving behind nutrient-rich organic end products for another component to sustain soil productivity. Selection of components in IFS model and their management is more critical; however, while selecting the components, it must be ensured that the interaction among components should be most complementary/supplementary rather than being competitive.

## 17.2 Strategies to Increase Farm Income

There are seven-point strategies being suggested for doubling the farmer's income by 2022 in India:

1. Focus on more crops, per drop of water.
2. Quality seed and soil health.
3. Investments in warehousing and cold chains.
4. Value addition through food processing.
5. Creation of a national farm market.
6. New revolutionary crop insurance scheme to mitigate risks at affordable cost.
7. Promotion of ancillary activities like cropping, poultry, beekeeping, fisheries, dairy, mushroom, vermicompost, kitchen garden, horticulture (fruits, vegetables, and floriculture) and boundary plantations, etc.

## 17.3 Status of Smallholders

As we know, Indian agriculture is dominated by small farms. Over the last 40 years (1971–2011), numbers of small holdings are increasing continuously with a rate of more than 2% annually, while the area under operation has only increased by 0.1%; as a result, the average farm size has gone down. Indian population is increasing at an alarming rate (1.2% annually); thereby, India will be the most populous country in the world by 2025. The growing population causes fragmentation of landholdings, and as a result, the average landholding of the Indian population has gone down from 2.3 ha in 1970–1971 to 1.2 ha in 2010–2011 and further reduced to 1.08 ha in 2015–2016. During the reported periods, the number of marginal farmers, those possessing cultivable landholdings of less than 1 ha, has increased from 51% to 68.4% (Table 17.1).

The data given in Table 17.1 and Table 17.2 indicate that not only the farm holding size continuously declined over the years, but inequalities in distribution of basic resources like land, labor, capital, energy, water etc. is also on the rise, and ultimately, the landlessness is the logical culmination of this process. With continuum of this process, the number of landless agricultural labor households has grown from 13 million in 1972 to 107 million in 2001 and counted 144 million in 2011. Consequently, in the coming years, there will be considerable food deficit for households in rural areas, and more land would be locked for self-consumption only. It is expected that in the coming years, food surplus we have today would rapidly decline with the growing urban population; hence, aggravate food insecurity may arise in the future. The data represented in Tables 17.1 and 17.2 revealed that from 1970 to 2015–2016, the share of small farms in crops production remained

**Table 17.2** Operational landholdings distribution in India (1970–2015)

| Year | Number of holdings ('000) | Average size (ha) | Marginal (%) | Small (%) | Semi-medium (%) | Medium (%) | Large (%) |
|---|---|---|---|---|---|---|---|
| 1970–1971 | 71,011 | 2.3 | 51.0 | 18.9 | 15.0 | 11.2 | 3.9 |
| 1980–1981 | 88,883 | 1.8 | 56.4 | 18.1 | 14.0 | 9.1 | 2.4 |
| 1990–1991 | 106,638 | 1.6 | 59.4 | 18.8 | 13.1 | 7.1 | 1.6 |
| 2000–2001 | 119,931 | 1.3 | 62.9 | 18.9 | 11.7 | 5.5 | 1.0 |
| 2005–2006 | 129,222 | 1.2 | 64.8 | 18.5 | 10.9 | 4.9 | 0.8 |
| 2010–2011 | 137,757 | 1.2 | 67.0 | 17.9 | 10.0 | 4.3 | 0.7 |
| 2015–2016 | 146.45 | 1.08 | 68.4 | 17.62 | 9.55 | 3.79 | 0.57 |

above 70% besides a significant ownership of livestock. The situation clearly indicated that farming system research (FSR) approaches may hold much significance and promise on such farms to boost up the production and self-sufficiency among the smallholders.

## 17.4 Challenges before Smallholders

Small farm holders have poor access to land, water, inputs, and credit besides technology and market facilities. Under the existing agrarian structure, most of the rural farm families are small and marginal and are living below the poverty line, with continued threats to their livelihood security characterized by low food security and income, unemployment, health problems, education, etc. Further, this section of farming community is also susceptible to natural vagaries like drought and flood that caused a large-scale migration of farmers to urban areas in search of livelihood opportunities. Due to the above factors, these categories of farmers have poorly adapted to the changed farming scenario, especially in the far remote areas of the country. It is quite obvious that small and fragmented landholdings do not allow farmers to maintain independent farm resources, viz., draught animals, tractors, bore wells/tube wells, and other sophisticated farm machineries, which are prerequisite for various cultural operations of agriculture. Moreover, most of these categories of farmers are illiterate or poorly educated or economically poor and generally work in resource-poor and risk-prone environments. At the same time, small and marginal farmers also remained ignorant about the advancements coming in the agricultural field since in the beginning, the focus had been on maximization of crop yields, and that too remained more centric to resource-rich farmers. In the post-liberalization era, new threats have emerged out in terms of sustainability issues of smallholders presently; smallholders also face some of the new challenges, viz., integration in value chains, liberalization and globalization effects, and market volatility besides vulnerability and adaptation to climate change (Thapa and Gaiha 2011). Nowadays, the concept of contract and commercial farming is gradually gaining popularity in

India; with this, the farmers may face some new challenges. In the present era, though agriculture is rolling at a faster speed by virtue of utilization of various chemicals, their adverse impact on environment created several problems including the global warming by which poor farmers of India are facing acute problem in agriculture and allied sectors. Since the poor rural masses are not proficiently using the available resources and solely remained dependent upon the artificial manufactures, thereby the cost of living is not only increasing day by day, but the cost on medical expenses also increased over a period of time due to the ill health of the farmers; as a result, no money was left with them to contribute for agricultural growth.

## 17.5 Necessity of Integrated Farming System

Since, it is clear from various estimates that more than 80% of farmers in India possess small or marginal holdings, hence, sustaining household food security would always remain the key issue for such farmers. Innovative technologies though proved to be technically sound appliances, at the same time they were recognized for their limited acceptance because these are mainly targeted to the resource-endowed production system and majority of farmers in India are very resource poor and thereby cannot afford the heavy cost involved in these techniques. Moreover, each farm has its own specific typology arising to variations in resource availability and family circumstance. Likewise, the biophysical, socioeconomic, and human characteristics of a farm are interdependent on time and space. Other factors like fragmented landholding, low level of mechanization, and poor economic conditions also forbid farmers to adopt innovative agricultural techniques. Since the landholding per farm family in India is continuously going down, which has reached from 1.15 ha in year 2010–2011 to 1.08 by year 2015–2016, hence, side by side, not only a significant rise in the number of small and marginal farmers is occurring, but the numbers of landless labor is also increasing at a very fast speed. The rest of the economic sectors of India are also not in the position to absorb the surplus manpower. In these circumstances, India has to survive with its small-sized farms for the next two decades, which is very difficult without following integrated farming system approaches. As the integrated farming system includes various farm components at one place, which makes it a labor-intensive system, hence, it is able to generate more jobs and therefore engage the farmer family effectively throughout the year on their farms. Integrated farming system is also an effective way to ensure profitability, balanced food, a clean environment, employment, regular income generation throughout the year, a high input-output ratio, sustainability, and ultimately upliftment of the rural masses. It is also a way to provide access to the best technology and markets. If diversified components in farming system were implemented, the new interventions enabled the farmers to gain food security, nutritional security, livelihood improvement, and sustainability. Therefore, it can be stated that integrated farming system is a prime necessity to achieve livelihood subsistence of the increasing population.

## 17.6 Integrated Farming System Model/Modules

Due to the continuous increase of input cost, today, agriculture becomes a less profitable occupation especially to those farmers who are solely dependent on agriculture for their food and nutritional security. Adoption of improved technologies at farm level may offer better opportunities to such farmers to enhance overall production and productivity of their farm, which ultimately caused an overall improvement in living standard of the farmers (Sivamurugan 2001). Presently, as compared to the past, farmer's purchasing power has also been increased due to increase output from various components of the farming systems (FS). Now, producers are endowed with sufficient information that made it easy to arrive at a decision to take appropriate combination of distinct components such as crops, diary, horticulture, fisheries, mushroom farming, beekeeping, kitchen gardening, backyard poultry, and value addition of farm base produces on a piece of cultivable land they possess. Thus, farmers can increase their income by selling the surplus produce in the market besides sustaining their livelihood development. In IFS adoption process, the farmers also acquired knowledge by getting exposure and through interaction with various entrepreneurs owing to be of different farm enterprises besides the effective use of natural resources, these are easily available in the farm and recycled the nutrients in the farm soils. That in turn ensures the creation of better awareness about the adoption of technology(ies) and ultimately leads to a sustainable production process by creating additional on-farm employment for better support of livelihood of poor rural farm families. Some of the prominent farming systems model/modules suggested for different agroclimatic zones are described below.

### 17.6.1 Model/Modules for Small-Scale Farming

Though every farmer has his own IFS model, it may not be adequate to fulfill all their demands at one place, so there is an urgent need to change the customs of farming and adopt extra integer of components, viz., diversified crop and livestock enterprises, to fetch some source of extra income for livelihood improvement and to curtail migration, child labor, and poverty, vis-a-vis build villages for their self-sustenance via creating assets such as roads, clean drinking water, soil and water conservation work, etc. Existing farming systems should be modified by keeping in view of rural livelihood requirements since peoples in rural areas are undernourished and devoid of sufficient food and calories as per requirement. In this respect, the ICAR-Indian Institute of Farming Systems Research, Modipuram, Uttar Pradesh, India, has developed various farming system modules and models by involving poor farm men, especially those residing in rural areas and who do not want to leave their traditional rehabilitations. The Integrated farming system models for small farmers were developed at district level by taking into consideration of climatic, edaphic, and social factors because districts in India are diverse in climatic factors; hence, model/module developed for a particular district may not be implantable to another. The developed models/modules were successfully being tested at the farmers' fields, and ample efforts were made to mitigate the constraints which caused hindrance in adoption progress. In general, it is observed that farmers still stick to traditional technologies in agriculture production system that caused decline in productivity, and now, the time has come to enhance the wisdom of farmer community to utilize various components of agriculture by including the other allied sectors. To enhance the skill of farmers about the integrated farming technologies, the developed models/modules are being tested at their farm and ample knowledge being provided by conducting training programs. Now, the time has come to characterize the local factors which are affected prevailing farming situation to improve the overall productivity and livelihood as well as to fulfill the Mahatma Gandhi dreams of new Bharat building where nobody should sleep hungry and thirsty. The integrated farming systems have been developed for smallholders on 1.5 ha of land in the western plain zone of Uttar Pradesh. Various modules have been evaluated for efficient exploitation of available limited resources, which are commonly accessible to farmers. The productivity of an integrated farming system arose several times as compared to existing farming due to association of nine components at one place. The another important integrated farming system model has also been developed for the marginal farmers of Upper Gangetic Plains region of Uttar Pradesh, the farmer who are having less than 1 ha of land, the components like crops, dairy, horticulture, fishery, mushroom, vermicompost and boundary plantation were comprised in the model. It was found that integration of various components was looked sufficient to provide the divergent farm commodities for the households and surplus produces for the selling market.

### 17.6.2 Models/Modules for Dryland Farming Systems

The dryland farming system is a complex system that interrelates matrix of soil, plants, animals, implements, power, labor, capital, and other inputs controlled by farm families and also influenced by varying degrees of political, economic, institutional, and social forces operated at many stages. In other words, it is defined as a unique and reasonably stable arrangement of farm enterprises that the household manages according to its physical, biological, economic, and sociocultural environment needs as per the household's goals, preferences, and resources. Conceptually, it refers to a set of elements or components that are interrelated themselves. The farmer is at the center of interaction, exercising control and choice according to the type and bearings of an interaction. It is a resource management strategy to achieve higher economic goals and sustained production to meet the diverse food demand of farm households besides conserving resources and maintaining a high level of environmental quality, for example, to integrate farm enterprises, viz., cropping systems, animal husbandry, fisheries, forestry, sericulture, poultry, etc., in such a way that farm resources could be utilized efficiently and in more fruit-bearing manner and in accordance to farmers' need and ultimately to make them prosperous. In India, nearly 100 m ha of land is under rainfed farming. Therefore, rainfed farming also plays an important role in Indian economy. Since moisture stress and deficiency of nutrients in dryland soil are the main constraints, hence, the integrated farming system in dryland area is characterized by low and unpredictable yield due to various causes such as inefficient use of rainwater and soil, sporadic use of synthetic fertilizers, lack of high yielding varieties, and not taking care of improved soil conservation measures (Singh et al. 2000). Poor inherent fertility status along with low water holding capacity of soil of dryland farming regions also contributes to poor crop yields; thus, the existing cropping systems in these areas lead to a high degree of uncertainty in yield, income, and employment (Singh 1995). The integrated farming systems approach is capable to bring out changes in farming technique therefore, productivity of available resources can be maximize via judicious combination of agricultural crops and other enterprises suited best to a specific agro-climatic situation and socio-economic status of the farmers and it would certainly improve the prosperity in the dry land farming (Radhamani et al. 2003). The current-day trend toward sustainable agriculture encourages the utilization of crop and its allied activities for enrichment of soil nutrients and water retention and to protect the environment over a longer period of time. The selection of enterprises must be based on the basic principle of minimizing the competition and maximizing the complementarities amid among enterprises. In Uttar Pradesh state, it was observed that crop +dairy + goat farming followed by crop + goat farming had the maximum potential (Singh and Sharma 1987). Likewise, Singh et al. (1988) also suggested that integrated farming system with goat and sheep rearing under dry conditions of India's Punjab region was a more profitable enterprise. Integration of dairy + biogas + silviculture for dryland condition and cropping + goat under rainfed condition was the finest models for the western zone of Tamil Nadu (Rangasamy et al. 1990). In Eastern India, where cereals and grain legumes were formed, an integral part of the model, raising small breeds of livestock and poultry in rainfed/dry land, was found profitable (Singh et al. 1993a, b). According to Phengvichith (1998), on-farm appropriate system-oriented technology should be generated to realize the potential contribution of livestock in a crop + livestock system to ensure social acceptability and economic viability. Predominance of milch cows, goats, and buffaloes along with crops in the dry land was observed more beneficial as reported by Radhamani (2001). For 1 ha area of dry land, integration of sorghum + cowpea (grain), sorghum + cowpea (fodder), and *Cenchrus glaucus* each in 0.33 ha intercropped in aonla (*Emblica officinalis*) with Tellicherry goat (five females and one male) in 0.01 ha area could be recommended against raising sorghum crop alone. Integration of goat (11 females and 1 male), rabbit (7 doe +1 buck), and pigeon birds (10 pairs) with crop component pearl millet (grain) + soybean (grain), maize (fodder) + cowpea (fodder), and *Cenchrus ciliaris* + *Stylosanthes scabra* (fodder crops) was found to be the best for model development on 1 ha dry land area of western zone of Tamil Nadu (Thirukumaram 2002). In dryland IFS model, crop module should be integrated with other modules like goat, pigeon, buffalo, agroforestry, and fish for livelihood sustenance to poor farmers (Esther Shekinah et al. 2005). Tellicherry breed of goat was maintained for meat production purposes. Buffaloes were maintained for milk production in the dryland farming model. The farm pond was dug for collecting runoff during rain that can be used in times of moisture stress vis-a-vis silt collection. Integrated farming system with two bullocks + one cow + one buffalo + ten goats along with poultry and duck is the most useful system for the marginal farmers in rainfed regions of Chhattisgarh as well as in Central India (Ramrao et al. 2006). The integrated farming system (IFS) approach with combination of crops, viz., rice, tomato, and cauliflower, along with non-crop enterprises like poultry, mushroom, and vermicompost were recognized as a sustainable system to give maximum net return and additional employment generation under rainfed agriculture in the Deogarh of Orissa (Barik et al. 2010).

### 17.6.3 Model/Modules for Landless Farmers

In Uttar Pradesh, nearly 27% of landless population engaged in various agricultural works for their livelihood survival. This huge population is trapped in poverty due to various reasons. National Sample Survey Organization (NSSO) conducted in 2011 revealed that more than 30% of households neither have land to cultivate nor owned or leased; thereby, they are facing certain problems, those linked to landless farmers of India. Livestock rearing is a main occupation for the survival and nutritional security of such farmers. The landless farmers in the country offer fodder to animals via collecting it from wastelands, roadside, canal banks, fallow lands, and top feeds (for small ruminants) as green fodder. Landless workers are also recognized as true cultivators because they get land from small and large farmers on lease via various modes like land-sharing practice (land is taken against the mutually agreed share of the produced grain), Honda farming (lands are obtained for a certain period after paying a fixed amount), etc. to earn their livelihood and for employment. Adoption of some of the unique approaches especially those that address issues of landless farmers and got linked to enhance the productivity of livestock could be a supportive mechanism for upliftment of economic conditions of such farmers. Certain vital activities such as providing health services for livestock, demonstrating fodder production technologies, supplying mineral mixture for dairy animals, and improving reproduction efficiency of livestock by means of different technologies may also be beneficial for them. Keeping few small ruminants also provides an excellent opportunity to earn some amount of supplementary income to such farmers; for instance, goat rearing can provide a sustainable livelihood for a family. Apart from goat, the landless householders can earn some short of additional income through poultry, mushroom farming, kitchen garden, value addition, and fishery. Livestock rearing is also a supportive system for agriculture production system because it provides good quality of manure as source of efficient nutrients supplement to the crop.

## 17.7 Added Advantages of IFS

Integrated farming system approaches are recognized to enhance small farm productivity and income via integration of crop-livestock production systems with added advantages of multiple livelihood opportunities through agro-processing and biomass utilization. Therefore, the integrated farming system is an essential tool to meet food production targets, reducing hunger, poverty, and rural unemployment. Improving small farm production and productivity via selecting suitable farming system as a single development strategy can make the greatest contribution to the elimination of hunger and poverty. Therefore, an integrated crop livestock/fisheries farming system has to be the way forward for the country. Some of the advantages of integrated farming system are discussed next.

### 17.7.1 Economic Contribution

According to Acharya et al. (1987), buffaloes had a significant role in financial advantage in both irrigated and unirrigated areas of the country. Pandey (1988) also advocated about the addition of buffaloes for improving income and employment generation with existing cropping system of entire India. Experiments conducted on a farm having sandy loam soil at Hisar in Haryana (India) also revealed a higher net return after adding buffalo and cow enterprises with crop component (Kadian et al. 1992). Arvind and Jain (1992) also recommended the adoption of buffalo component on small-scale farms in Punjab to increase farm income and labor employment. In the semiarid tropics of India (SAT), Deoghare and Bhattacharya (1993) reported that keeping goat and sheep contributed nearly to 30% of the total farm income and hence recognized the most valuable source of income. Buffalo's milk yield can be sustained after integrating sorghum and cow pea in a ratio of 2:1, along with the crop component (Gupta et al. 1994). Rangasamy (1995) pointed out that integration of sorghum grain crop (0.20 ha) + sorghum fodder crop (0.20 ha) + subabul and *Cenchrus ciliaris* (0.20 ha) as an intercrop + *Acacia senegal* and *Prosopis cineraria* (0.20 ha) along with Tellicherry goats (20 females and 1 male) increased the net income of the farmers. Out of the total income generated from this integrated farming model, nearly 59% of income was derived from the goat component alone. The additional net income of ₹ 5672 $ha^{-1}$ $year^{-1}$ and an additional employment of 314 man-days $ha^{-1}$ $year^{-1}$ were achieved by following integrated farming system (IFS) in comparison to the cropping system alone. Small ruminants like sheep and goats also form an important economic and ecological niche in Asian mixed farming systems (Devendra 1998). A considerable increase in income of small and marginal farmers of southern zone of Tamil Nadu state of India was achieved after integration of cropping with rainfed fruit trees and goat rearing in dry land (Senthilvel et al. 1998). San and Deaton (1999) reported nearly 38% increase in net income after integration of sheep in rubber plantation at a smallholder farmer's field. Maximum net return of ₹12,593/− was received from 1 ha of wheat-sugarcane cropping farm when integrated with a buffalo in Rohtak (Singh et al. 1999).

Basavaraj and Gangadharappa (1999), while working on profitability of different IFS enterprises, recorded an average net profit of ₹42,984 ha$^{-1}$ after integration of sugarcane, dairy, and sheep components. In the silvipasture-based dryland farming system, rearing of goat recorded higher income followed by milch cows (Vairavan et al. 2000). In western zone of Tamil Nadu, Radhamani (2001) concluded that integration of crops along with fruit trees and goats gave higher net return in comparison to the sole crop component under rainfed situation, whereas in southern Tamil Nadu region, where black soil do exist and rainfed situation also prevailed in such situations, planting of some leguminous trees such as *Leucaena leucocephala*, *Acacia senegal*, and *Prosopis cineraria* along with perennial grass component on an area of 1.6 ha and rearing about six goats on that piece of land was recognized to yield an additional income of ₹ 12,500/year (Ramasamy et al. 2007).

## 17.8 Vertical Farming

As compared to land-based farming, vertical farming technology can ensure crop production all-year round in non-tropical regions, maintaining higher productivity. Generally, hilly lands are 3 to 4 times less productive as compared to the plain fertile land; therefore, vertical farming in these areas could be a best option to increase production. Under vertical farming the crops being grown in multilayers on hills by utilizing precise space, light, nutrients, and temperatures therefore owing to be of several stories layers of crops at distinct elevations leads to increase per unit yield and as a result also increase income of household. Since, vertical farming being conducting by including multiple crops growing at different layers therefore if any one of crop fails due to some reason the left over crop can generate some income. In this farming system approach, an intensive crop coverage occurs that caused minimal runoff of water from soil surface; hence, this does not only control soil erosion but also contribute toward the saving of nutrients. Since in vertical farming strategy advanced techniques are involved, therefore, high-value crops such as fruits, vegetables, and edible mushrooms can be grown easily for maximization of farm profit. Vertical farming can also be adopted for raising livestock, poultry, and fisheries indoors. It is also suitable for growing shade-loving plants, viz., large cardamom, turmeric, and ginger, besides cucurbitaceous crops like bottle gourd, pumpkin, chow-chow, and sponge gourd on a constructed bamboo machan. Bamboos are available at a cheaper rate; hence, it doesn't involve much cost. Aside from providing support to cucurbitaceous crops, the lower portion of the machan provides a congenial environment for cultivation of spices like turmeric and ginger due to enough shade. To aid in growth, cucurbitaceous crop seeds are placed into a small pit prepared at a distance of 2–3 m intervals. Due to higher coverage of the foliage of cucurbitaceous crops, less weed infestation as well as 65% higher production of turmeric and ginger was obtained as compared to open cultivation. Among all the combinations of cucurbit crops, bottle gourd was found more suitable as compared to others like sponge/smooth gourd and chow-chow for vertical intensification with ginger and turmeric. Since vertical farming is conducted under controlled growing conditions, therefore, pests can be controlled without the use of pesticides. In vertical farming, biological control methodologies are much effective in controlling insects like ladybugs. Vertical farming also protect the crops from extreme weather like droughts, hail, and floods. Hydroponic growing techniques can also be utilized efficiently in vertical farming by utilizing 70% less water than normal agriculture. Moreover, deploying vertical farms on a large scale could result in a significant reduction in air pollution and $CO_2$ emissions. The current model for crops grown in vertical farms focuses on high-value, rapid-growing, small-footprint, and quick-turnover crops, such as lettuce, basil, and other salad items.

## 17.9 Small Farm Mechanization

Keeping in view of doubling farmer's income by 2022, farm mechanization also play a grave role because it would not only bring down the cost of cultivation to the tune of 20–25% but also increase production by 20%. Hence, in order to resolve the labor problem in India, farm mechanization is vital to promote both agriculture and allied sectors. Small farm mechanization also plays a key role in water management at farm since water is one of the most important commodities for crop production. The depletion of groundwater level and uneven distribution of rains are the main factors affecting water availability and yield of various crops. Conservation of some of the resources such as water gaining much importance due to unsustainable use, environmental pollution and the health of ecosystems. Therefore, keeping in view of water preservation, a lot of efforts are being made to harness water efficiency. The concept of more crops per drop of water came into existence. Efficient irrigation systems including sprinkler irrigation, drip irrigation, etc. have been developed and are being utilized successfully to grow more crops by using very less amount of water as compared to flood irrigation. By following certain tillage practices like zero tillage, soil moisture is being conserved, and equipment, viz., tractor-operated no-till drill, were developed for successful cultivation. Apart from this, some more instruments were developed for various works. A laser level is being developed to achieve precise fine levelling with desired grade. Tractor-operated rotavator is developed to prepare seedbeds in a single operation in both dry and wetland conditions and also found suitable for incorporating straw and green manuring. The impact of revolving blades of rotavator sheared the soil and made fine therefore pulverize the soil uniformly. Tractor-drawn strip-till drill helps to sow wheat crop after paddy without any prior seedbed preparation, whereas tractor-operated bed former cum seeder has been developed for sowing of wheat. The machine can make three beds in a single run, and the width of each bed is adjustable (35–45 cm).

## 17.10 Resource Recycling

Crop and livestock components at smallholder farming systems generally complement and in no way compete with each other in respect of utilization of available natural resource. On small holder farms, fodder crops raised to feed the animals therefore, nutrients removed by these crops from soil got replenished back to the soil to a greater extent in form of cattle manure (Nair Vikaraman et al. 1976). Manure obtained from goat rearing is also recognized a good source of plant nutrients hence it's recycling to soil enhanced crop productivity and also play key role in building up the soil fertility (Senthilvel et al. 1998). Recycling of crop-livestock wastes materials in dry land and rainfed areas also contribute in enhancing the soil fertility status via nutrient recycling besides the appreciable organic carbon enrichment in the soil (Sajise 1998; Devendra 2000). It was seen that a pair of draught cattle, if integrated in the farm, ensures the availability of nearly 12 tons of manure that can be diverted to crop-grown areas to maintain crop productivity and soil fertility (Alam et al. 2000). Thus, integrated farming system, offers us an excellent opportunity in terms of organic recycling as a result small and marginal farmers remained less depend on external purchase of inputs. Integrated farming system also offers good scope for recycling of crop by products and residues as a source of feeding materials to the livestock and in turn livestock produced valuable waste in form of dung and urine those can be converted to good quality of manure to maintain crop productivity and soil fertility. Application of 50% nitrogen through fertilizer and 50% through goat manure revealed to enhance soil fertility status and also was recognized as a better option of recycling manure to crops (Radhamani 2001). Jayanthi et al. (2003) also reported the effect of integration of dairy and goat components along with cropping, and this kind of farming system arrangement revealed to utilize available resources in most beneficial ways. Therefore, the big advantage of crop and livestock component accumulation is that crop by-products are being utilized as good resources for animal feed and manure received from livestock enterprises are being recycled as a source of nutrients to crops; hence, in this, nutrients absorbed by crops from the soil get harvested back to the soil. An enhanced residue generation and increased efficiency of waste recycling was obtained via integration of crops with pigeon, goat, buffalo, and agroforestry and farm pond combination (Esther Shekinah et al. 2005). The highest amount of residue addition to the tune of 11,583 kg/year$^{-1}$ with plant nutrient values of 105.9, 46.2, and 76.9 kg NPK, respectively, was found possible with crop + pigeon + goat + buffalo + agroforestry + farm pond integration (Ramasamy et al. 2007) via recycling of crop residues and animal manure from integrated farming system components about 5.3, 1.6 and 3.7 tons of compost, vermicompost and bio-compost, respectively were prepared successfully and the prepared manures were found capable enough to supply 26.0, 22.3 and 26.0 kg NPK, respectively to field and fodder crops from obtained bio-compost and 39.4, 10.5 and 18.0 kg NPK, respectively to vegetable crops from vermicompost in one acre of land area (Jayanthi et al. 2007). Under irrigated upland conditions, integration of seasonal vegetable (bitter gourd, tomato, bottle gourd) with food crops (rice, potato, onion), goat, and vermicompost resulted in higher productivity than cropping alone. It was also observed that recycling of vermicompost and goat manure in the system not only reduced the cost of cultivation but also improved soil health (Shivani et al. 2010). Thus, it can easily be concluded that various enterprise combinations in a farming system mode were linked to a higher nutritive output as compared to cropping alone.

## 17.11 Employment Generation

Various enterprises linked in the integrated farming system in turn were also linked heavily to generate extra employment. This approach proved more fruit-bearing in dryland areas where farm families remained unemployed almost for two thirds portion of a year since crops in those areas occupied only a part of the year, i.e., the monsoon season. Generally, crop-centric farming alone is recognized to generate employment nearly to 400 man-days in a year, whereas if this system is integrated with six buffaloes in farming system mode, then 904 man-days in a year were generated (Pandey and Bhogal 1980). Goat farming is also an effective way to generate more employment opportunities in dryland areas of the country (Rai and Singh 1982; Kale 1999). Sheep and goat nurturing on grazing lands or roadside or wastelands had always been a profitable occupation (Nehra et al. 1992 and Das 2001) and was hence recognized as a constant and regular source of employment and income to landless and marginal farm families. A highest labor employment of 58% was recorded with rearing of large flock size of goat extensively on grazing lands (Singh 1996a, b). Average labor employment of, e.g., 23.3, 1.9, 33.1, and 41.1% per household per year was recorded, respectively, from goat, sheep, buffalo, and crop farming (Deoghare 1997). In arid zones of Rajasthan, additional employment was generated by adoption of silvi-pastoral or horti-pastoral systems with sheep and goat rearing (Gajja et al. 1999). Radhamani (2001) calculated the additional employment generation of 314 man-days ha$^{-1}$ year$^{-1}$ via integration of farming system with crop + goat under rainfed farming situations. In the same year, Sivamurugan also found that the highest employment of 875 man-days year$^{-1}$ can easily be generated via integration of crops with dairy + biogas + mushroom components. Integrated farming system in dry lands done by following sorghum +cowpea, *Leucaena leucocephala* + *Cenchrus ciliaris*, and *Acacia Senegal* + *Cenchrus ciliaris* along with integration of goat produced an additional employment of 113 man-days ha$^{-1}$ annually. Compared to sole crop components, an additional employment of 562 man-days was generated via integration of crop + dairy + biogas + silviculture + spawn production under irrigated lands of dry areas. Rearing a herd of nearly 200 goats under integrated farming system was found to provide full-time employment for two persons throughout the whole year (Ramasamy et al. 2007).

## 17.12 Conclusion and Way Forward

As coated by “Mahatma Gandhi” just as the whole universe is contained in the self, so has India contained in the villages. Rural development generally refers to the process of improving the quality of life and economic welfare of people living relatively in isolated and sparsely populated areas. A suitable integrated farming system (IFS) could be a sound approach for the overall development of a large group of farmers (87%) in India because farming families are influenced heavily by political, economic, institutional and the factors those operates at the farm level. Integrated farming system approaches can also control migration of enormous human population from villages to urban cities. For efficient utilization of existing resources and farm by-products, resource-poor farmers are now heartened to integrate crops with other components and land-based vocations with non-land-based enterprises via different types of IFS models. The ancillary activities in IFS models are characterized by low investment, higher profit, homestead, and family labor. Various resource conservation technologies have also been evolved to follow the “more crops per drop” theory. The farming system approach has gained acceptance in poverty elevation, food security, competitiveness, and sustainability in production. The IFS focuses on judicious combinations of distinct enterprises and effective recycling of farm-based residues for better management of available resources. It helps small and marginal farmers generate more income and employment for family members in regular as well as off-seasons. It comprises crops, livestock, poultry, fishery, duckery, mushroom farming, beekeeping, production, apiculture, agroforestry, and sericulture, by which total biomass production per unit area can be increased. Backyard poultry and vermicompost can be added to IFS models to increase farm income and strengthen livelihood. IFS also encompasses the objective of conservation of existing natural resources and their efficient utilization for sustainable growth of productivity as well as profitability. Thus, the IFS approach focuses on selected interdependent, interrelated, and interlinked enterprises of crops, animals, and other related subsidiary occupations. In this process, beekeeping, fisheries, mushroom cultivation, and space-conservative subsidiary businesses are added to give additional high-energy food without affecting production of main food grain crops. It can be taken up in all types of social systems and can also be implemented in both rainfed/dryland and irrigated areas, where the farmers need more output from the limited resources. Thus, monocropping system, which restricts productivity per unit of land, can be substituted by the farming system approach. It is dissimilar from corporate farming, owing to the integration of different complementary components. Moreover, the IFS process is aimed at strengthening nutritional security and employment generation. Thus, an integrated farming system approach may not only be a boon for the poor famers in India but also be recognized as an effective tool for providing self-sufficiency in food grain and nutritional security. The entire philosophy of an integrated farming system relies on the better utilization of time, money, resources, and family laborers of farm families. The entire philosophy of an integrated farming system relies on the better utilization of time, money, resources, and family laborers thereby farm families ensures scope for gaining employment throughout the year on their farms that on turn ensures good income and a better standard of living. Time has come now to incarnate the small farms to adopt farming system approaches, and scientists, administrators, and planners should also think of developing programs and encouraging farmers to opt for farming system approaches.

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# Unlocking Potential of Dryland Horticulture in Climate-Resilient Farming

# 18

Lopamudra Jena, Heera Lal Atal, Subhadarsini Pradhan, Subhasmita Sahu, Meikam Ichancha, Daripalli Srilakshmi, Tapas Mandal, and Jyoti Prakash Sahoo

## Abstract

Dry lands are areas characterized by poor availability of soil and water resource; occupy about 41.3% of the land surface in world, contributing to 44% of cultivated systems around the globe; and also are home to about 2 billion people. In order to obtain sustainability, it is essential to boost the productivity of dry lands with increased widely spread growth. Unlike irrigated horticulture, achieving considerable yield profit is difficult in dryland horticulture. Henceforth, it is essential to plan for gradual increment in crop yield by making more efficient use of resources available in semi-arid and arid zones. To mitigate the harmful effect of changing climatic conditions on productivity as well as quality of horticultural crops, there is requisite to establish substantial adaptation strategies. Attention must be given towards the development of production systems, which is necessary for increased water use efficiency, adoptable to hot and dry conditions. Dryland horticulture not only secures sustainable production from the field but also, to a certain extent, aids in utmost utilization of available natural resources such as water, light and land. Efforts can be put forth to create awareness among farmers as well as fruit and vegetable growers regarding innovative technological approaches such as use of high yielding and suitable cultivars for dryland areas and their multiplication, water harvesting practices, integrated nutrient management, mulching, technologies to increase shelf life of fruits and value addition of

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the products and marketing. This, in turn, will help increase economic status and livelihood security of horticultural farmers of arid and semi-arid regions.

**Keywords**

Horticulture · Dryland · Climate change · Arid and semi-arid regions

## 18.1 Introduction

Nature-dependent lands are enriched with horticultural biodiversity and biotic-abiotic stress resistance and have inherent potential for production of quality fruits, vegetables, flowers and spices. Low and unpredictable rainfall, frequent droughts, temperature extremes, low humidity, poor soil and water quality, high evapotranspiration rate and high wind velocity characterize the dry region (Wale and Dejenie 2013). These conditions, on the other hand, can be used to boost productivity by means of improved horticultural techniques and interventions that will result in higher return by using wind and solar energy, human labour and expanding infrastructure, all of which benefit the farming community's income. The crop chosen for these areas should possess the ability to withstand abiotic stress conditions and have its reproductive phase timed to coincide with the greatest moisture availability period (Roy and Roy 2019). Now, it is ascertained that there is a lot of scope available for a quantum leap in production of horticultural crops in dryland regions.

Dry lands cover 41.3% of the global land surface, with arid and semi-arid regions accounting for the majority (25.80%) and contributing to 44% of the cultivated system. The developing nations occupy 72% of dry lands worldwide, while industrialized nations contribute for the rest, which is 28%. Traditionally, dry lands have been predominantly used for livestock, although they are now increasingly being turned into horticultural lands. The dryland population is 2.1 billion, which means it is home to one out of every three people on the planet today. Desertification may wreak havoc on nearly a billion of the world's poorest and marginalized populations, who reside in most endangered areas (Ramakrishna and Rao 2008). As far as India is concerned, arid region alone occupies about 12.02% of the geographical area. The hot dry region covers around 31.7 million hectares, primarily in the states of Rajasthan, Gujarat, Andhra Pradesh, Punjab and Haryana, with a population of nearly 20 million people and an average density of 61 people per square kilometre. The state-wise coverage of area falling under arid zones in India is cited in Fig. 18.1. Important districts coming under the potential arid zones in India are indexed in Table 18.1. Extremely low rainfall, low soil moisture and high evapotranspiration are primary land degradation factors in dry regions, while indirect drivers include poverty, a low rate of adoption of advanced technologies, prevalence of traditional marketing system and socio-political dynamics (Saroj 2018).

Indian horticulture has made remarkable progress towards food self-sufficiency. It has emerged as the best alternative for diversification in facing the needs for food, nutrition and health care, as well as offering greater returns to farmland and more

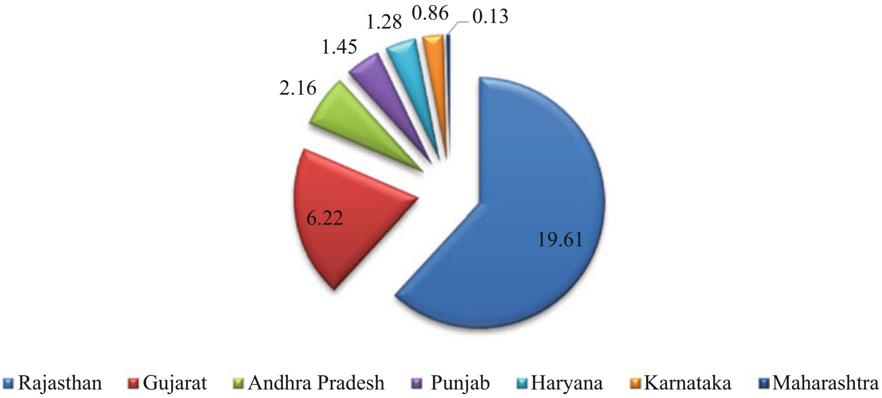

**Fig. 18.1** State-wise area coverage under arid zones in India (mha) (Source: FASAI 2022)

**Table 18.1** State-wise area coverage under arid zones in India (Source: FASAI 2022)

| Sl. no. | State | Area covered under arid zone in India (mha) | Percentage area out of the total zone | Important districts coming under |
|---|---|---|---|---|
| 1. | Rajasthan | 19.61 | 62 | Bikaner, Jaisalmer, Jodhpur, Jalore, Ajmer, Barmer, Jhunjhunu, Ganganagar, Sikar, Churu pali, Nagaur |
| 2. | Gujarat | 6.22 | 20 | Jamnagar, Banaskantha, Mehsana, Kutch, Surendranagar, Amreli, Jungadh |
| 3. | Andhra Pradesh | 2.16 | 7 | Cuddapah, Anantapur, Kurnool |
| 4. | Punjab | 1.45 | 5 | Bhatinda, Ferozpur |
| 5. | Haryana | 1.28 | 4 | Hissar |
| 6. | Karnataka | 0.86 | 3 | Bellary, Dharwad, Raichur, Chitradurga |
| 7. | Maharashtra | 0.13 | 0.4 | Sholapur, Dhulia, Satara, Nashik |

employment opportunities. The potential horticultural crops suited for dryland cultivation in different states of India coming under arid zone are cited in Fig. 18.2. In terms of increasing output, productivity and export, India's investment in horticulture has paid off, with the country emerging as the second largest fruit and vegetable producer in the world. This changing scenario is ascribed to technical advancements and endeavours for holistic development. On the other hand, the challenges on our front are much pronounced than earlier and need to be addressed with strategized approaches using revolutions in science and technology. Previous accomplishments have attested the country's ability in addressing such difficulties and have necessitated investment and deliberate efforts in a coordinated manner (Hussain and Khan 2022).

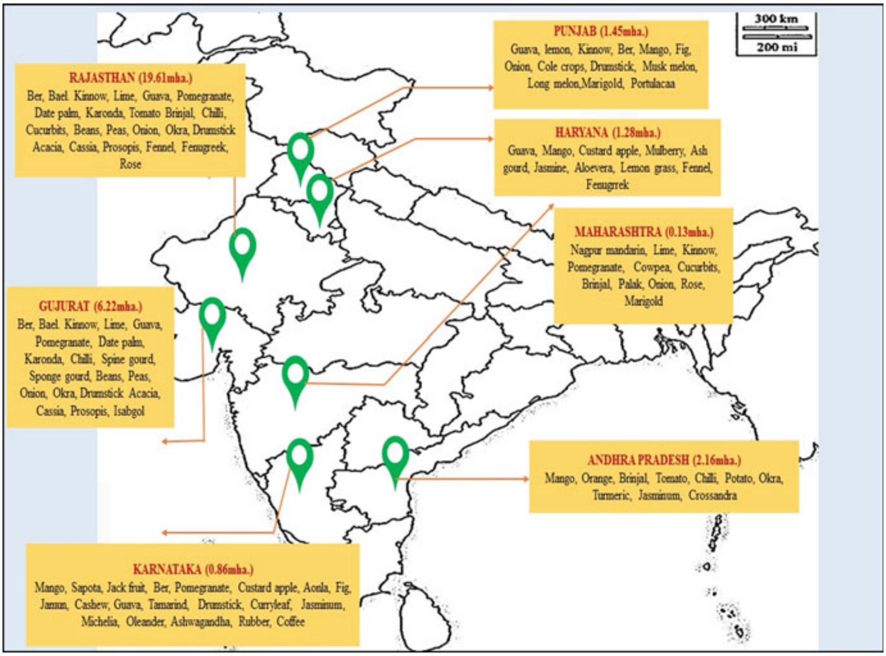

**Fig. 18.2** Potential horticultural crops suitable for dryland cultivation in different states of India coming under arid zone (Source: FASAI 2022)

Climate aberration is one of the major significant threats to plant biodiversity, consequently affecting plant development, yield and quality parameters (Chary et al. 2022). Global climate change, under the current scenario, is a huge menace to socioeconomic activities such as agriculture and forestry, as well as biodiversity and ecosystems (Lepetz et al. 2009). The climate regime has deteriorated over the past five decades, primarily due to anthropogenic causes, both locally and worldwide. By the twenty-first century, the Intergovernmental Panel on Climate Change predicts hotter days and nights, as well as a reduction in precipitation in desert area. The change in climatic conditions is said to have an adverse effect on the biodiversity of arid regions (Charan and Sharma 2016), as well as crop productivity and yield. It also has adverse effects on horticultural crops because of alternations in air temperature, precipitation, moisture content in soil, humidity and wind speed (Malhotra 2017; Saroj 2018), thereby reducing crop output and quality.

## 18.2 Problems Associated with Dryland Farming

When crop plants are taken under dryland farming, they are often encountered with several risk factors during their growth and development period. Some of the major challenges faced in dryland cultivation are problematic soil, moisture stress, low and

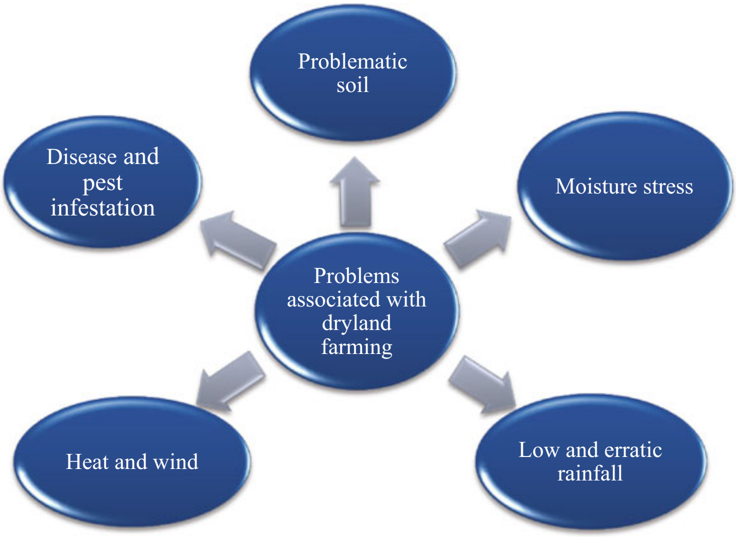

**Fig. 18.3** Different problems associated with dryland farming (Source: FASAI 2022)

rainfall, heat, wind and infestation of diseases and pests, *i.e.,* both abiotic and biotic factors (Fig. 18.3). They are further discussed underneath.

### 18.2.1 Soil

In terms of nutrient availability, water holding capacity and other factors, arid soils are severely deficient. The 'desert soils' and 'grey brown soils' falling under the order Aridisols are generally light grained soils, found mostly in the north-western arid regions. The majority of arid regions (around 64.6%) are dense, with soils containing just 3.2–4.0% clay and 1.4–1.8% silt (Osman 2013). Apart from that, around 5.9% of the land is occupied by hard pan bearing soils, 5.6% by hills and pediments, 6.8% by alluvial dunes and 1.6% by sierozems extending from Haryana and Punjab soils. Red sandy soils cover a considerable portion of the dry region, and some parts of the dry region in peninsular India are occupied by mixed black soils (Srinivasarao et al. 2021). Organic matter levels in the soils range from 0.03% in bare sand dunes to 0.1% in stabilized dunes. Total available boron and potassium are abundant in soils, whereas nitrogen, phosphorus and other trace elements such as iron, zinc and copper are scarce. Soils coming under these regions are often characterized with high salinity. The organic matter content in the soil is less, and therefore, the fertility potential is likely to be low in dryland zones. There is a problem of leaching losses of nutrients, which decrease soil fertility drastically. Soil salinity and alkalinity are also some serious problems in the drier regions (Naik and Sharma 2021).

### 18.2.2 Water

Water is essential for the survival of all living entities. Plants have become adapted to thrive and reproduce in semi-arid, dry and even desert environments through various mechanisms. However, when aridity spikes up, fewer and fewer species can sustain, thus resulting in a reduction in biomass. Water, which falls in dryland regions, is squandered, because of the insufficient amount of water that enters the soil, or due to quick penetration through the porous soil, or as a consequence of running off of the water (Mishra and Tripathi 2013). Because of inadequate surface and subsurface drainage, ground water is not only scarce but also salty in the arid region. Irrigation water resources include surface wells, seasonal rivers and rivulets and certain water storage structures collecting runoff (e.g., nadis, tankas and khadins), as well as canal irrigation (Krishnappa et al. 1999; Rathore et al. 2017). As a result, water resources in the dry region are restricted, allowing only 4% of the land to be irrigated. In India, irrigated area constitutes 33%, whereas 67% is covered by dryland and rainfed area. The maximum irrigated area will be achieved 50% after the full utilization of all sources of irrigation. After full exploitation of dry land, it may contribute up to 75% of total food production.

### 18.2.3 Rainfall

The yearly average rainfall in dry regions is relatively less and unpredictable, ranging from 100 mm in Jaisalmer's north-western sector to 450 mm in Rajasthan's eastern boundary or arid region. The major amount of precipitation falls in the north-western dry region between July and September in about 19–21 rain spells. Appropriate technology is required to boost productivity in the dry region due to low and uneven rainfall patterns (Unger et al. 2006). Water is a valuable input in the country's hot desert regions, so using a micro-irrigation system to save water and increase output is recommended.

### 18.2.4 Heat and Wind

Heat and wind have the primary effect of raising the temperature of plant leaf surfaces, which increases the rate of water evaporation. Crops may also suffer mechanical damage as a result of the wind. Windbreaks and shelter belts can help mitigate the effects of strong winds (lines of trees perpendicular to the way of prevailing winds). *Tamarindus*, *Casuarina* and *Eucalyptus* are some beneficial tall species which can be used efficiently for this purpose. Trees and other vegetations of various heights can be used to constitute a windbreak. A windbreak is useful over an area 2.5 times the height of the tree as a general rule. However, it may be mentioned that a windbreak may compete with the major crops for water, light and nutrients (Unger et al. 2006). As a result, in each given area, the benefits of a windbreak must be evaluated against the disadvantages. Frost is also a constraint in some parts of the desert region during the winter season, affecting plant vegetative development, productivity and fruit quality, particularly in aonla, ber and lasoda. There are limited heat-tolerant varieties available in arid horticulture crops that will aid in achieving higher production in dry arid regions.

### 18.2.5 Disease and Pest Infestations

Disease and pest infestations are abundant in the drier regions. These, on the other hand, may be considerably different from those found in wetter areas. In sandy soils, nematodes are a common problem. No common rules are beneficial, and indeed, agriculture anticipates diseases and pests and their parasite. In these areas, unpredictable and constant rain is a vital cause of a variety of diseases and pests. For arid climate, the cultivar which is biotic and abiotic stress resistant is desired for sustainable production.

## 18.3 Climate Change's Impact on Growth and Development of Crops

In dry places, the influences of climatic anomaly on horticultural growth, development and yield are particularly alarming. Climate aberration in dryland zones characterized by elevated temperatures will decrease crop productivity by shortening crop duration (using fewer natural resources), increasing interception of solar radiation and harvest index, accumulation of biomass and raising moisture stress in crop plants as a result of escalated evapotranspiration demand (Chary et al. 2022). A modest fluctuation in rainfall will only have a minimal influence on productivity of crop until the change is significant. However, a rise in temperature of 3.3 °C reduces crop productivity by 27% on average under good management (Wani et al. 2009).

At the same time, an increase in rainfall of 11% will have minimum impact. Similarly, frost and hailstorms in India's north-western states between December and March have been recorded to harm cultivated crops such as phalsa, date palm and lasoda. There is also a change if flowering time coincides with fruit maturity during the monsoon season in June–July, which reduces future output and quality. A significant rise in temperature (>40 °C) in March can sometimes harm arid vegetables, particularly cucurbits. Arid veggies will perish if the monsoon breaks early and the rains stop for an extended period of time. Such meteorological anomalies have an impact on horticulture crops all around the world, not just in arid regions. It is crucial to take into account that the influence of climate aberration at recent crop management levels would become negligible if such anomalies continue to occur (Jat et al. 2012).

This means that as crop management is being improved to obtain higher yields and food security, the influence of climatic anomaly will become more and more significant. It is now apparent that climatic irregularities will have a negative effect on crop productivity, and as a result of which, food security will be threatened

(Dixon et al. 2014). Aside from the impacts of climate change on growth and development of crop, moisture availability and other factors, there is a considerable likelihood of increasing soil deterioration as a result of the loss of organic matter from soil caused by rising temperature regimes (Bellard et al. 2012). This may result in considerable reduction in yield potential than what is being currently predicted. Adaptation to climate change is thus no longer a secondary or long-term response option, but rather a prominent and urgent necessity, especially for those populations already vulnerable to the effects of current climatic threats (Burton et al. 2003). To reduce the influence of change in climatic conditions on crop output, soil health and water availability, a holistic approach is required.

## 18.4 Strategies for Resistance to Climate Change-Related Adversity Mitigation and Adaptation

In the current scenario of climate change along with the need to meet the food requirement of the burgeoning population and a highly deteriorated resource base (land and water), the current practice of crop production in dry lands is no longer an option. Appropriate long-term coping methods for dryland agriculture must be developed in the near future to maintain food security for a large population on a sustainable basis (Bellard et al. 2012). Particularly the farmers and society as a whole have traditionally tried to adapt to climatic stressors by employing tactics such as mixed cropping, altering types and times of planting (crop rotation) and therefore extending their sources of profit (Mwale 2018). Such adaptation measures will require to be addressed in the future, alongside new ideas to deal with the climatic irregularities.

Given the restrictions of both ongoing climate-induced production risk and the anticipated change in nature of that risk in the future, a two-pronged strategy, also mentioned to be the ‘twin pillars’ of climate change acclimatization, is now widely acknowledged (Cooper and Coe 2011). Such a method acknowledges short- and medium-term adaptation tactics. According to Cooper and Coe (2011), in the short term, because rainfed farmers are already vulnerable to current weather abnormalities and shocks associated with them, it is critical to assist them in building livelihood resilience by adapting better with current climate-induced threat as a pre-requisite to adjust with climate aberration in the future (Nkonya et al. 2015). Even though this was said in the African context, it applies equivalently to India, where adoption of enhanced agricultural technologies, particularly in dryland farming, is still low. Also, it is widely acknowledged that growers will need to adapt their farming techniques to a fresh set of weather-related hazards and possibilities in the medium to long run (Nidumolu et al. 2015).

## 18.5 The Biodiversity of the Hot Arid Zone

India is one of the richest ethno-botanical emporia on the planet. Rural and tribal populations have valuable information regarding the use of indigenous plants in hot desert regions, just as they do in other parts of India (Meena, Meena and Yadav 2010). Aside from identification of plants as food, fodder, medicine and so on, there is also analogous experience with life sport species for emergencies such as drought and famines, which so far have been underutilized. Several studies contributed to ethno-botanical features of western Rajasthan's 'Thar Desert'. Traditional species of economic importance of the hot arid region have immense value as they have evolved naturally so as to survive under abiotic stress conditions. They have evolved to cope with a variety of natural risks brought on by global climate change, as well as pest and disease infestations.

Certain arid plants' essential oil/gums appear to have a critical role in shielding them from drought and higher temperatures. Herbal nutraceuticals, antioxidants, adaptogen herbs and other natural health products are gaining popularity around the world for human and animal health. The adapted species of the hot arid zone have distinct characteristics of which some may be crucial in the future due to climatic changes or the advent of new diseases. The 'Thar Desert' features a wide range of floral diversity, including dry grassland, trees, prickly plants and economically important desert fruits and vegetables. Khejri (*Prosopis cineraria*) is one of them, and it is known as Kalpavriksh. It is regarded as the lifeline of India's hot dry zone, and it is an important part of the arid environment.

The presence of ephemeral rivers such as the Luni, Sookdi, Ghagghar, Bandi and Jojri plays a very crucial role in the micro-climatic conditions of the regions, which they pass through, thus, affecting the vegetation of the 'Thar Desert', and it is one of the most important geological features of the 'Thar Desert' (Charan and Sharma, 2016). The desert area yielded a total of 62 families, 157 genera and 206 species. Fabaceae has the most species (29), followed by Poaceae (26); Asteraceae (15); Amaranthaceae (10); Cucurbitaceae (9); Convolvulaceae (6); Boraginaceae; Euhorbiaceae and Lamiaceae (5 each); Acanthaceae, Brassicaceae, Capparaceae and Zygophyllaceae (4 each); Solanaceae, Asclepiadaceae, Apocynaceae, Menispermaceae, Tiliaceae, Malvaceae and Chenopodiaceae (3 each); and Aizoaceae, Molluginaceae, Cleomaceae, Cyperaceae, Hydrocharitaceae, Moraceae, Caesalpinioideae, Nymphaceae, Pedaliaceae, Plantaginaceae, Rhamnaceae, Salvedoraceae and Tamaricaceae (2 each), while the rest of the 29 families are represented with one species. According to Charan and Sharma (2016), herbaceous vegetation (60.10%) was the most common type of vegetation in the 'Thar Desert', followed by shrubs (16.26%), trees (14.29%) and climbers (9.36%) (Roy and Roy 2019). A list of potential fruits, vegetables, ornamental, spices and medicinal and aromatic crops along with their well-suited cultivars for dry zone cultivation is provided in Tables 18.2, 18.3, 18.4, 18.5, and 18.6, respectively.

**Table 18.2** List of potential fruit crops and cultivars for dryland horticulture

| Sl. no. | Crop name | Scientific name | Family | Chr. no. (2n) | Varieties suitable for dry land | Promising genotypes evaluated | Characteristics | References |
|---|---|---|---|---|---|---|---|---|
| 1 | Ber (Indian jujube) | *Ziziphus mauritiana* | Rhamnaceae | 24 | Goma Kirti, Gola, Seb, Umran, Banarasi Kadaka, Kaithali, Mundia, Goma Kirti, Thar Malti, Narendra Ber Sel-1 and 2 | Thar Bhubharaj, Thar Sevika, Tikadi | Early maturing with yield capacity of 65–70 kg/tree; frost/low temperature tolerant during winter arid regions | Sharma et al. (2018) |
| 2 | Aonla (Indian gooseberry) | *Emblica officinalis* | Phyllantaceae | 18, 28 | Banarasi, Chakaiya, NA-6 (Amrit), NA-7 (Neelam), NA-10, Kanchan, Krishna, Anand-1, Anand-2, Lakshmi-52, BSR-1 | Goma Aishwarya | Bears profusely under arid conditions, early variety with a yield potential of 105 kg fruits/tree | Singh et al. (2011) |
| 3 | Bael | *Aegle marmelos* | Rutaceae | 36 | NB-5,NB-9, Pant Aparna, Pant Urvashi, Pant Shivani, Pant Sujata, CISH Bael-1 & CISH Bael-2, Godhra, Goma Yashi | Thar Neelkanth<br>Thar Divya | No influence of aberrant agroclimatic conditions on plant, fruits less hampered by sunscald, yield 75 kg/plant<br>Drought tolerant, better performance under less precipitation and high temperature | Singh et al. (2011) |
| 4 | Pomegranate (Anar) | *Punica granatum* | Punicaceae | 18 | Ganesh, Dholka, Jalore Seedless, Mridula, Phule Arakta, Ruby, Amalidana, G-137, Jyoti, Basin Seedless, | Goma Khatta | Popular choice for arid regions, preferred for Anardana purpose | More et al. (2008) |

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|---|---|---|---|---|---|---|---|---|
| | | | | | Bhagwa, Super Bhagwa, Solapur Lal | | | |
| 5 | Lasoda (Gonda) | *Cordia dichotoma* | Boraginaceae | 48 | Karan Lasoda, Maru Samridhi | Thar Bold | Suitable for block plantation, component of agroforestry system in dry and arid zones, yield—1.5–2.0q fruits/plant/year | More et al. (2008) |
| 6 | Khirni | *Manilkara hexandra* | Sapotaceae | 26 | Thar Rituraj | Thar Rituraj | Precocious bearer, semi-dwarf suitable for high-density planting, free of pests and diseases | Singh et al. (2020) |
| 7 | Karonda | *Carissa carandas* | Apocyanaceae | 12 | Thar Kamal | Thar Kamal | Comes of well under rainfed conditions of hot arid ecosystem, fruit yield 13 kg/plant | Singh et al. (2020) |
| 8 | Jamun (Java plum) | *Syzygium cumini* | Myrtaceae | 40 | Thar Karanti, Arabhavi-1 and 2 | Goma Priyanka | Enriched fruit quality with a yield potential of 60 kg/plant, drought tolerant | Singh et al. (2020) |
| 9 | Chironji | *Buchanania lanzan* | Anacardiaceae | -- | Thar Priya | Thar Priya | Cultivated in tribal belt of MP and Gujarat, suitable for high-density planting | Sharma et al. (2018) |
| 10 | Tamarind (Imli) | *Tamarindus indica* | Caesalpiniceae | 24 | PKM 1, Pratisthan, Yogeshwari, Ananta Rudhira, | Goma Prateek | Choicest pod size and quality, an average of 58.50 kg fruits can be obtained from a 9-year-old plant | Singh et al. 2020 |

(continued)

**Table 18.2** (continued)

| Sl. no. | Crop name | Scientific name | Family | Chr. no. (2n) | Varieties suitable for dry land | Promising genotypes evaluated | Characteristics | References |
|---|---|---|---|---|---|---|---|---|
| 11 | Wood apple (Kainth) | *Feronia limonia* | Rutaceae | 18 | Thar Gaurav | Thar Gaurav | Better shelf life under limited rainfall conditions of western India | Vashishtha, (2005) |
| 12 | Custard apple (Sugar apple) | *Annona squamosa* | Annonaceae | 14,16 | Balanagar, Mammoth, Island Gem, APK (Ca) 1, Phule Janki, Aruppukkottai | Arka Sahan | Excellent choice for drought conditions | Saroj et al. (2020) |
| 13 | Fig (Anjir) | *Ficus carica* | Moraceae | 26 | Dinkar, Dianna, Conadria, Excel | Poona Fig | Grown commercially in Punjab, fruit weight—42 grams | Singh et al. (2020) |
| 14 | Phalsa | *Grewia subinaequalis* | Tiliaceae | 36 | Thar Pragati | Thar Pragati | Early bearer, dwarf, drought friendly, suitable for HDP | Singh et al. (2020) |
| 15 | Mulberry | *Morus alba* | Moraceae | 308 | Thar Lohit, Thar Harit | Thar Lohit | Tolerant to both frost -2 °C and high temperature (48 °C) conditions, yield—32 kg/plant | Saroj et al. (2020) |
| 16 | Manila tamarind (Madras thorn) | *Pithecellobium dulce* | Fabaceae | 26 | PKM (MT) 1 | PKM (MT) 1 | Prolific yielder, comes up well in sandy, saline and alkaline conditions | Vashishtha (2005) |
| 17 | Mahua | *Madhuca indica* | Sapotaceae | 24 | Thar Madhu | Thar Madhu | Dwarf, precocious bearer, suitable for HDP | Singh et al. (2020) |

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|---|---|---|---|---|---|---|---|---|
| 18 | Mango | *Mangifera indica* | Anacardiaceae | 40 | Dashehari, Kesar, Badami, and Raspuri | Mallika | Field tolerance to varied agroclimatic conditions, yielding 5–9 tonnes/acre of fresh fruits | Singh et al. (2020) |
| 19 | Guava | *Psidium guajava* | Myrtaceae | | Sardar | Allahbad Safeda | Hardy, moisture stress resistant, yield potential—20–25 tons/ha | NIC, Karnataka State Unit |
| 20 | Cashew | *Anacardium occidentale* | Anarcardiaceae | 42 | Ullal series, Chintamani-1 | Priyanka | Prolific bearer (17.03 kg/tree), bold nuts, drought tolerant, resistant to biotic stress | NIC, Karnataka State Unit |
| 21 | Date palm (Khajur) | *Phoenix dactylifera* | Arecaceae | 28 | Halawy, Barhee, Medjool, Khalas, Khuneizi, Khadrawy, Zahidi | Thar Sobha | Thorn-less tree, drought-loving plant | Saroj et al. (2020) |

**Table 18.3** List of potential vegetable crops and cultivars for dryland horticulture

| Sl. no. | Crop name | Scientific name | Family | Chr. no. (2n) | Varieties suitable for dry land | Promising genotypes evaluated | Characteristics | References |
|---|---|---|---|---|---|---|---|---|
| 1 | Guar (cluster bean) | *Cyamopsis tetragonoloba* | Fabaceae | 14 | Pusa Mausami, Pusa Navbahar, Durga Bahar, AHG-13, Goma Manjari | Thar Bhadavi | Heavy yielder (65–125 q/ha), pod yield 75 g/ plant, nine clusters/plant | Sharma et al. (2018) |
| 2 | Cowpea | *Vigna unguiculata* | Fabaceae | 22 | Pusa Barsati, Pusa Naubahar, Pusa Komal, Anand Cowpea-1 | Arka Garima | Excellent field tolerance to heat and low moisture stress | Sharma et al. (2018) |
| 3 | Dolichos bean (Indian bean) | *Lablab purpureus* | Fabaceae | 22, 24 | Arka Vijay, Arka Jay | Thar Kartiki, Thar Maghi | Pod yield—110 q/ha; pod yield—113.25 q/ha | Sharma et al. (2018) |
| 4 | Sword bean | *Canavalia gladiata* | Fabaceae | 22, 44 | SBS-1 | Thar Mahi | 40% higher pod yield than local, pod yield—56q/ha, 1.73 kg/ plant approx. | Sharma et al. (2018) |
| 5 | Cucumber | *Cucumis sativus* | Cucurbitaceae | 14 | Olympic, Dasher II, Thunder | Solan Kheera Hybrid-2, NS-46 | Low temperature tolerant; heat resistant | Pathak and Kaur (2022) |
| 6 | Kachri | *Cucumis callosus* | Cucurbitaceae | 24 | AHK-119, AHK-200 | AHK-119 AHK-200 | Predominantly grown in Rajasthan; fruit yield varies from 100 to 120q/ha | Saroj and Choudhary (2019) |

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|---|---|---|---|---|---|---|---|---|
| 7 | Pumpkin | *Cucurbita moschata* | Cucurbitaceae | 20 | Arka Chandan, Gujarat pumpkin-1, CO-2 | Thar Kavi | Drought tolerant, compact plant growth; thus, more plants/ha can be taken, moderately resistant to pests and diseases | Singh et al. (2020) |
| 8 | Bottle gourd | *Lagenaria siceraria* | Cucurbitaceae | 22 | Pride of Gujarat, Pusa Naveen and Arka Harit | Thar Samridhi | High yield potential (240–300 q/ha) under hot arid environment, fruit weight 450–700 g, first harvest after 55 days | Sharma et al. (2018) |
| 9 | Bitter gourd (Jhaar karela) | *Momordica balsamina* | Cucurbitaceae | 22 | Preethi, Priya, CO-1, MDU-1, Arka Harit, Punjab Kareli-1 | Punjab Jhad Karela-1, Punjab-14 | Comes up well under arid regions, with an average yield of 35–50 q/ha | Pathak and Kaur (2022) |
| 10 | Sponge gourd | *Luffa cylindrica* | Cucurbitaceae | 26 | NHSG-5026 | Thar Tapis | Short duration (110–115 days), heat-tolerant variety with a yield of 145.80 q/ha | Saroj and Choudhary (2019) |
| 11 | Ridge gourd | *Luffa acutangula* | Cucurbitaceae | 26 | NHRG-1001 | Thar Karni | Early maturing, tolerant to high temperature (42 °C) and diseases under field condition | Mallikarjunarao et al. (2015) |
| 12 | Ash gourd | *Benincasa hispida* | Cucurbitaceae | 24 | Pusa Ujwal, Kashi Ujwal, CO-1 and 2 | Thar Sundari | Parthenocarpic variety, better drip irrigation, tolerant to dry climate (40–42 °C) | Saroj and Choudhary (2019) |
| 13 | Spine gourd | *Momordica dioica* | Cucurbitaceae | 22 | Arka Bharat | Indira Kankoda (RMF-37) | Can be cultivated successfully in dry regions of Maharashtra, | Saroj and Choudhary (2019) |

(continued)

**Table 18.3** (continued)

| Sl. no. | Crop name | Scientific name | Family | Chr. no. (2n) | Varieties suitable for dry land | Promising genotypes evaluated | Characteristics | References |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Uttar Pradesh, Karnataka, etc. yielding 10–20 q/ha | |
| 14 | Pointed gourd | *Trichosanthes dioica* | Cucurbitaceae | 22 | Arka Neelachalkirti Padra local, Rajendra Parwal-1 and 2 | CHPG-15 | Field resistance; yields 29–32 tons/ha of fruits | Mallikarjunarao et al. (2015) |
| 15 | Khejri (Sangri) | *Prosopis cineraria* | Fabaceae | 24 | Thar Shobha<br>Red Podded Khejri | Thar Shobha | Tolerant to extreme edapho-climatic condition, hardy plant, bears flowers and fruits under dry conditions | Saroj and Choudhary (2019) |
| 16 | Drum stick | *Moringa oleifera* | Moringaceae | 28 | GKVK-1, Dhanraj, PKM-1 and 2, Urugam DTS-2 | Thar Harsha | Drought hardy, tolerant to heat and moisture stress, matures late with a yield of 45–48 kg green pods/plant | Singh et al. (2020) |
| 17 | Muskmelon | *Cucumis melo* | Cucurbitaceae | 24 | Pusa Sharbati, Hara Madhu, Punjab Sunehri, Durgapura Madhu | Pusa Madhuras, Gujarat Muskmelon-3 | Yield potential 150–170 q/ha, field resistance to major pests and diseases | Choudhary et al. (2018) |
| 18 | Snap melon | *Cucumis melo* var. *momordica* | Cucurbitaceae | 24 | AHS-10, AHS-82 | AHS-10<br>AHS-82 | Extra early variety with yield 225–230 q/ha<br>Sweeter than previous, profuse growth, yield 250 q/ha | Saroj and Choudhary (2019) |

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|---|---|---|---|---|---|---|---|---|
| 19 | Long melon (Kakri) | *Cucumis melo* var. *utilissimus* | Cucurbitaceae | 24 | Thar Sheetal | Thar Sheetal | Set fruits at high temperature (42 °C) during summer under hot arid conditions of Rajasthan, Punjab | Mallikarjunarao et al. (2015) |
| 20 | Watermelon (Mateera) | *Citrullus lanatus* | Cucurbitaceae | 22 | Sugar Baby, Durgapura Meetha | Thar Manak | Drought hardy, suitable for cultivation in arid zones during rainy season, yield potential 400–500 q/ha | Saroj and Choudhary (2019) |
| 21 | Amaranth | *Amaranthus* spp. | Amaranthaceae | 32–38 | CO-1, 3, 4 and 5 | Pusa Kirti, | Yield of greens is 500 q/ha | Rai et al. (2011) |
| 22 | Palak | *Spinacia oleracea* | Amaranthaceae | 12 | Pusa Harit | Thar Hariparna | Early plant growth, consistent after several plucking, good yield (3.45 kg from 2 m × 2 m plot) with limited irrigation drip, channel, etc. in north-west Rajasthan | Rai et al. (2011) |
| 23 | Brinjal | *Solanum tuberosum* | Solanaceae | 24 | Doli-5 and Gujarat Brinjal hybrid-1, Bundelkhand Deshi | Thar Rachit | Very early (45 days after transplanting), raised well under limited rain (<250 mm), yields about 3–4 kg/plant under hot-arid environment | More et al. (2008) |

(continued)

**Table 18.3** (continued)

| Sl. no. | Crop name | Scientific name | Family | Chr. no. (2n) | Varieties suitable for dry land | Promising genotypes evaluated | Characteristics | References |
|---|---|---|---|---|---|---|---|---|
| 24 | Tomato | *Lycopersicon esculentum* | Solanaceae | 24 | Gujarat tomato-1 and Gujarat Tomato-2, Arka Vikash | Thar Annant | Suitable for high temperature and water-scarce condition, yielding 52–55 tonnes/ha | Rai et al. (2011) |
| 25 | Chilli and capsicum | *Capsicum annuum* | Solanaceae | 24 | Pusa Jwala, Mathania, Pant C-1, GVC-111, GCV-121, GCV-131, Bharat | Arka Lohit | Drought tolerant, more capsaicin content, prolific bearer | More et al. (2008) |
| 26 | Okra | *Abelmoschus esculentus* | Malvaceae | 130 | Punjab No. 13, Punjab Padmini, P-7,GO-2, GO-5, Parbhani Kranti | Gujarat Anand Okra-5 | 142 q/ha fresh fruit yield, immune to YVMV, low sucking pest population | More et al. (2008) |
| 27 | Onion | *Allium cepa* | Alliaceae |  | Arka Kalyan, MST-46, MST-42 | Udaipur-102 and 103 | Yield potential—300–500 q/ha, excellent keeping quality | Singh (2010) |
| 28 | Potato | *Solanum tuberosum* | Solanaceae | 48 | Alpha, Bintej, Kufri Sindhuri | Kufri Sheetman | Highly resistant of late blight potato, frost resistant, yield—200–250q/ha | Pandey et al. (2011) |
| 29 | Sweet potato | *Ipomoea batatas* | Convolvulaceae | 90 | VLS6, IGSP 10, IGSP 14, | Sree Bhadra | Short duration, with yield 23 tons/ha | Singh, 2010 |

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| 30 | Curry leaves | *Murraya koenigii* | Rutaceae | 18 | Suhasini | Suhasini | Better adapted to climate change, characteristic small leaves rich in medicinal properties and intense odour | More et al. (2008) |

**Table 18.4** List of potential ornamental crops and cultivars for dryland horticulture

| Sl. no. | Crop name | Scientific name | Family | Chr. no. (2n) | Varieties suitable for dryland | Promising genotypes evaluated | Characteristics | References |
|---|---|---|---|---|---|---|---|---|
| 1 | Bougainvillea | *Bougainvillea* spp. | Nyctaginaceae | 34 | San Deigo Red, Delta dawn | Barbara Karst | Popularly used for xeriscaping, drought and high temperature tolerant | Kimberly Gomes (2016) |
| 2 | Rose | *Rosa* spp. | Rosaceae | 14–56 | New dawn, Lady Hillingdon | Pushkar Rose | Popular commercial rose variety of Rajasthan | Stan (2022) |
| 3 | Marigold | *Tagetes* spp. | Asteraceae | 18 | Sunset giant, Cracker Jack, Bonanza, Disco | Moonstruck Yellow, Big Duck | Blooms heavily in dry soil, field resistant to major pests and diseases | Turner (2021) |
| 4 | Portulaca | *Portulaca grandiflora* | Portulacaceae | 36 | Sundial, Sundance, Calypso | Moss Rose | Capable of thriving well in nutrient-poor dry soil | Garden Lovers Club (2022) |
| 5 | Adenium (Desert Rose) | *Adenium obesum* | Apocyanaceae | 22 | Double Black Asia, Yellow Fragrance | Red Picotee | Drought loving, shade tolerant | Martin and Orgogozo (2013) |
| 6 | Cactus | *Opuntia* spp., *Echinocereus* spp., etc | Cactaceae | 22 | Bunny Ear Cactus, Angel Wing, Hedgehog Cactus, Sempervivum | – | Drought tolerant, withstand intense heat | Lisa Taylor (2022) |

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|---|---|---|---|---|---|---|---|---|
| 7 | Lavender | *Lavandula* spp. | Lamiaceae | 18 | Anouk, Silver Anouk, Blue Cushion | Phenomenal; Munstead, Hidcote | Suitable for hot arid zones; suitable for cold arid zones | Garden Lovers Club (2022) |
| 8 | Geranium | *Geranium* spp. | Geraniaceae | 28 | Cardinal Red Improved, Chocolate mint, Shocking Pink, Flamingo Rose | Strawberry Sizzle, Violet | Heat tolerant, hardy requiring low maintenance | Garden Lovers Club (2022) |
| 9 | Periwinkle | *Vinca rosea* | Apocyanaceae | 34 | Cora Apricot, Heat Wave series | Nirvana | Heat tolerant, disease resistant | Liu et al. (2021) |

**Table 18.5** List of potential spice crops and cultivars for dryland horticulture

| Sl. no. | Crop name | Scientific name | Family | Chr. no. (2n) | Varieties suitable for dry land | Promising genotypes evaluated | Characteristics | References |
|---|---|---|---|---|---|---|---|---|
| 1 | Cumin | *Cuminum cyminum* | Apiaceae | 14 | GC-4 | CZC-94 | Earliness, short duration, requires minimal irrigation, free from major pest and diseases | Lal et al. (2014) |
| 2 | Fennel | *Foeniculum vulgare* | Apiaceae | 22 | Ajmer Fennel-1, RF-125, Hissar Swarup, CO-1 | Gujarat fennel 1 and 2 | Reasonably drought resistant, bushy with yield potential of 1700 and 2400 kg/ha | Lal et al. (2014) |
| 3 | Fenugreek | *Trigonella foenum-graecum* | Fabaceae | 16 | Ajmer fenugreek-4, Lam Selection-1, Hissar Solnali, Rmt-1 | Rajendra Kranti | Profuse yielder 12.50q/ha, drought loving | Lal et al. (2014) |
| 4 | Coriander | *Coriandrum sativum* | Umbelliferae | 22 | Rajendra Swati, Gujarat Coarinder-1 and 2, CO-1 and 3 | CO-2 | Drought tolerant, dual purpose, yield—600–700 kg/ha | Lal et al. (2014) |
| 5 | Ajwain | *Trachyspermum ammi* L. | Apiaceae | 18 | Ajmer ajwain-93, Lam Selection-1, Lam Ajowain-2 | Ajmer Ajwain-1 | Suitable for moisture stress conditions, bears 219 umbels/ plant | Dr. YSRHU Hortiportal |
| 6 | Nigella | *Nigella sativa* | Ranunculaceae | 12 | Ajmer nigella-20, Azad Kalongi, AN-1 | Ajmer Nigella-1 | Preferred for hot semi-arid regions of India, resistant to root rot, seed yield 8–12 q/ha | Malhotra (2004) |

**Table 18.6** List of potential medicinal and aromatic crops and cultivars for dryland horticulture

| Sl. no. | Crop name | Scientific name | Family | Chr. no. (2n) | Varieties suitable for dry land | Promising genotypes evaluated | Characteristics | References |
|---|---|---|---|---|---|---|---|---|
| 1 | Isabgol | *Plantago ovata* | Plantaginaceae | 8 | Gujarat Isabgol-1, Niharika, EC-124345, TS-1-10 | Gujarat Isabgol-2 | Hardy and prolific yielder at 1000 kg seeds/ha | Meena and Yadav (2010) |
| 2 | Aloe | *Aloe* spp. | Asphodelaceae | 14 | Cape aloe (*Aloe ferox*), Sudan aloe (*Aloe sinkatana*), Lavender star | Stone aloe (*Aloe petricola*) | Thrive well in rocky soil | Becca Badgett (2021) |
| 3 | Senna | *Cassia angustifolia* | Fabaceae | 28 | Anand Late selection, Sona | KKM-1, ATLF-2 | Hardy, less water needed, rich in medicinal values | TNAU Agritech Portal (2021) |
| 4 | Palmarosa | *Cymbopogon martini* | Poaceae | 20 | Tripta, Trishna, PRC-1, Rosa Gross-49a | IW-31245 | 20–25 tons of herbage yield | TNAU Agritech Portal (2021) |
| 5 | Lemongrass | *C. flexuosus* | Poaceae | 20 | NLG-84, Pragati, Jama rosa, RRL-16, Cauvery | Sugandhi | Can thrive well with lifesaving irrigations, oil yield 80–100 kg/ha | TNAU Agritech Portal (2021) |
| 6 | Vetiver | *Vetiveria zizanioides* | Poaceae | 20, 40 | Bharatpur type | Hyb-8 | High seed setting with vigorous roots | Lavania (2008) |

## 18.6 Criteria for Crop and Variety Selection

Careful selection of variety is of prime importance, as varieties performing well in irrigated or high-rainfall locations may as well be unsuited to dry land environments (Kumar et al. 2021). Several trials on dryland farming have failed, owing to a lack of understanding the criteria for variety selection. Dryland farming requires a wide range of varieties:

Dwarf cultivars with a smaller leaf surface area and fewer stomata or sunken stomata will have less transpiration.

Crops that can complete their vegetative development and reproductive phase during maximum moisture availability period may be chosen.

Crops or cultivars with deep, prolific and efficient root systems will improve moisture utilization.

Early- and quick-maturing types are essential for the crop to develop before the warmest and driest period of the year and mature before moisture reserves are depleted (escape mechanisms).

Plants with high bound water in tissues, thick cuticle, wax coating and pubescence (ber, phalsa) are promising.

Plants suitably adapted to shallow soils, gravelly, rocky and undulating barren lands (bael, pomegranate, aonla, cactus, succulents, etc.).

Crop cultivars that are resistant and adaptable to biotic and abiotic stress conditions.

## 18.7 Principles of Dryland Farming Techniques

### 18.7.1 Prevent a Crust at the Soil Surface

The beating action of raindrops tends to break down clods and disperse the soil particles. A rough, cloddy surface is created via tillage, which extends the time it takes for rain to break down the clods and seal the surface. Stubble mulch can be created on the surface after harvesting. This type of material not only keeps raindrops from falling on the soil directly but also slows the water flow down the hill, lengthening the time it takes to absorb it. The amount of water that runs off should be reduced. When waterlogging is not an issue to deal with, the runoff of water and its attendant erosion must be checked.

### 18.7.2 Reducing the Moisture Loss from Soil

Each grain is surrounded by a continuous film of water in the soil. Water is pushed up from below to replenish evaporated water near the surface, weakening the layer. Wilting does occur, when the water film is too thin for absorption by the plant roots. Tree or shrub shelter belts check wind speeds and cast shadows, which can decrease the rate of evaporation by up to 30% and lessen wind erosion. Mulching reduces wind velocity at the surface and lowers soil temperatures. Plant numbers and spacing are lowered in dry farming so that less number of plants will compete for soil moisture.

### 18.7.3 Reducing Transpiration

All growing plants use transpiration mechanism to take water from the soil and evaporate it through their leaves and stems. Some crop varieties are known to have smaller number of leaves, lesser leaf surface area, less stomatal count and stomata remaining closed during stress conditions, thus effectively reducing moisture loss.

## 18.8 Climate-Resilient Technological Interventions

### 18.8.1 Summer Fallow

When there is not enough rain, all of the dry-farming concepts of water conservation and usage will not aid in crop development. However, where the soil depth surpasses 18 inches (450 mm), it has been demonstrated that it is possible to store water as soil moisture from one year to the next by using suitable summer fallow procedures. Up to 75% of incident water may be retained at a soil depth of 1015 feet; however, 20% to 40% is more common (Aldababseh et al. 2018). Drought-induced starvation has been nearly eradicated in India where families have regularly set aside 5–6 acres each year for summer fallow.

### 18.8.2 Bunding

For abnormal slants, it is prescribed that for each drop of two feet, bunds of 18–24 inches in stature should be developed. It may be mentioned that even when area is decently level, a 12-inch-tall bund in each 250 feet is still found valuable (Aldababseh et al. 2018). Abundant stormwater can be discharged by developing periodic waste weirs with a sill of one-half bund stature. This will hold water and minimize the misfortune of surface soil loss. The outlets or waste weirs ought to be built of stones. Construction of crescent bunds at down side of pit and half-moon bund at slopes is quite beneficial in steep and undulating lands. Contour bunding is practised in relatively penetrable soils, whereas clay and black cotton soils are exceptions because of the water stagnation problem. Also a record of lowest soil loss @0.3 t/ha has been reported by Kale et al. (1993) in contour bunding as compared to 18.92 t/ha in control plots.

### 18.8.3 Agro-horticulture (Intercropping)

Most of the fruit trees grown in dry lands take approximately 5–8 years to cover the interspaces available. Further, in arid fruit trees like ber, pruning is advocated every year, so in the available interspace between the fruit plants, intercrops can be taken up successfully and profitably in a system named agro-horticulture. The crops raised in the interspaces must be generally short duration and of low stature, so that there will be no competition with the main fruit plants for nutrients, moisture and light. Agro-horticulture system at Hyderabad consisting of ber as main crop and vegetables as intercrops has resulted in higher remunerations than ber alone (Meng et al. 2004).

### 18.8.4 Water Management

#### 18.8.4.1 Water Shed Management

Much of the investigations taken up regarding rainfed farming in India can be related to preservation of soil and rainwater and dry spell sealing, which is a perfect tactic for acclimatizing to climate alterations (Venkateswarlu and Shankar 2009). Imperative innovations incorporate in situ water preservation, harvesting and recycling of rainwater, productive utilization of irrigation water, energy-efficient agriculture, vital productivity in agribusiness and usage of bad quality water. Watershed management has numerous components, which offer assistance both in adjustment and relief. Soil and water conservation approaches, like agricultural ponds and check dams, help control runoff and reduce floods during heavy rains (Mishra and Tripathi 2013).

#### 18.8.4.2 Rainwater Conservation and Harvesting

These include in situ and ex situ rainwater conservation for recycling to irrigate rainfed crops. The main contributor of irrigation in agriculture is enhanced ground water consumption and pumping water from deep tube wells. Surface rainwater storage in dug-out ponds is promoted, and low-lift pumps are utilized to lift that water for supplemental irrigation, which can lessen reliance on ground water. According to one estimate, around 28 million hectares of rainfed land in the eastern and central states have the ability to create 114 billion cubic meters of runoff, which may be utilized to provide supplementary irrigation to approximately 25 million hectares of rainfed land (CRIDA 2009). A total of 50 million agricultural ponds are required to store this amount of rainfall. It is typically one of the foremost imperative methodologies as it not only controls runoff and soil erosion but also contributes to climate alteration reliefs (Bhattacharyya et al. 2016). Conjunctive utilization of surface and ground water is a vital technique to relieve climate anomalies (Sharma et al. 2010). Inventive approaches in ground water sharing can contribute to equitable water distribution and decreased energy usage in pumping.

#### 18.8.4.3 Improved Irrigation Systems and Micro-irrigation

Irrigation water availability is a significant limiting input for agricultural output in dry environments where rainfall is scarce and subterranean water is brackish. In situ moisture conservation, as well as water harvesting and recycling, is thus very critical in arid horticulture (Mittal and Purohit 2006). Water delivery by pitchers (followed at CIAH, Bikaner for cactus pear), double-wall pots or trickle units (supply water at the functional root zone, thus contributing to water use efficiency), based on the agro-climatic parameters of the region, is deemed superior than the traditional ring basin and flooding techniques of irrigation followed during the orchard establishing period. Water consumption efficiency may be increased by cutting off evaporation losses (Permatasari et al. 2021). Drip or sprinkler irrigation is the most suited controlled irrigation technology for cucurbits, flowers and fruit crops grown in arid circumstances. Single lateral lines with online drippers were discovered to be the best for various cucurbitaceous vegetable crops such as kachri, snapmelon, muskmelon, long melon, bottle gourd, ridge gourd and watermelon (mateera), whereas in ber, pomegranate, date palm, double dripper lines are preferably used for uniform water distribution to the crops (Sharma et al. 2010). Fruit output increased by 25–30% in these crops as compared to the channel irrigation technology used in dry environments. A complete production technology based on drip irrigation has been developed and recommended for commercial cultivation of arid zone vegetables based on seasonal agro-climatic and weather conditions, crop potentiality and available resources (More et al. 2007). Drip irrigation, also known as micro-irrigation, saves 30–70% of irrigation water while increasing production by 25–80%.

### 18.8.5 Mulching

Mulching is the application of any substance on the surface of the soil. Mulching is a crucial agronomic practice that not only prevents the kinetic energy of raindrops and protects soil from erosion but also favours infiltration and decreases runoff and evaporation misfortunes (Krishnappa et al. 1999). Several organic mulches such as dry leaves, straw, hay, local weeds, crop residues, etc. have been found to be quite efficient in decreasing dissipation losses (Permatasari et al. 2021). Weed growth suppression, erosion control and organic matter incorporation into the soil are some other important features associated with mulching practice (Gupta 1995). A well-kept stubble and soil mulch can hold up to 20–70% of rainwater collected until the following year in an area free of growing vegetation. In ber orchards of western India, mulching with black polythene is quite remunerative. Although locally available organic mulches are quite cheaper than polythene mulches, these need proper care to maintain effective cover thickness. In Andhra Pradesh, Tamil Nadu and Karnataka, sapota farmsteads are being hugely provided with leaf mulch for soil moisture conservation purpose, whereas in Maharashtra, considerable benefits are harnessed by mulching with sugarcane bagasse in pomegranate, fig and custard apple. Significant increment in aonla production with paddy straw mulching was reported under arid and semi-arid environment of Gujarat (Singh 2010).

### 18.8.6 Use of Plant Growth Regulators and Chemicals

External applications of natural plant hormones as well as synthetic PGRs (plant growth regulators) are acknowledged to increase the fruit set and production and hasten uniform ripening for quick and easy harvest in arid conditions. Mepiquat chloride may act as a bio-regulator, accelerating the generative stage in vegetables. It induces dark green colouration of leaves and shortens internodal length. In water deficit conditions, potassium acts as shield to plants by participating in the trade of cytoplasmic $K^+$ (potassium) ions with stomatal $H^+$ (hydrogen) ions, thus boosting stomatal pH and advancing photosynthesis. This foliar application essentially diminishes transpiration rate, which may be because of enhanced stomatal resistance, leading to cellular moisture conservation ensuring high relative water content.

Application of 4–6% kaolin, 0.5–1.0% liquid paraffin and 1.5% power oil through foliar spray after periodic showers in low precipitation ranges significantly diminishes plant water loss (Pareek and Sharma 1991). Proline build-up was as well more noticeable in potassium chloride, which makes a difference inside the channelling of protein assimilation framework for drought resistance. Minimizing transpiration setbacks through the use of anti-transpirants (low concentration stomata closing substances such as PMA, alkenyl succinic acids and Atrazine; film-forming substances such as Mobi leaf, hexadeconal and silicons; reflectant types such as kaolin, celite, etc.), growth inhibitors (use of Cycocel diminishes lodging and increases yield) and stretching wind breaks (favouring the air resistance to water vapour).

### 18.8.7 Plant Architecture and Canopy Management

The plant canopy is quite essential in enhancing the quality criterion of crop production in fruit trees. The practice involving management of canopy structure has been employed in guava at the CISH (Central Institute for Subtropical Horticulture), Lucknow, and for citrus at NRC (National Research Centre), Nagpur, for boosting harvest and quality produce. Preparing trees in their early stages of development gives them a well-built framework and a strong stature. The bushy pomegranate must be trained in such a way where three to five stems are kept from the earth level, whereas single stem training with three to four primary branches is followed in other fruit trees. Pruning, on the other hand, is required to control the regenerative period of plants. Pruning of ber is done in Tamil Nadu in January, in Maharashtra by April end and in North India by May end.

The past season's primary branches are pruned, removing all side shoots and retaining back 15–25 nodes, depending on area, cultivar and age and tree build-up. Frequent light pruning accounts development of long non-flowering branched that can be eliminated by pruning half of the shoots, leaving 1 or 2 nodes that will encourage fresh growth for fruiting in the subsequent year. Pruning time in phalsa must be adjusted as per the blooming period, thus resulting in more number of fruiting shoots. In north India, pruning of old phalsa bushes to a height of 150 cm is advocated yearly once during the month of January and yearly twice, i.e., during December and June in south India. Pruning from earth level is done to either renew senile bushes or to train new plants into bush shape. In the dry environment, foliar defoliation of lasoda trees in December–January yields early blooming and fruit production. Chemical defoliation in pomegranate has been quite helpful for bahar treatment (Mishra et al. 2020).

### 18.8.8 Integrated Nutrient Management

Plants require supply of balanced nutrients at the right time, taking age and growth factor into consideration. The application strategies are exceptionally crucial in terms of supplement accessibility by the plants. Apart from 10–15 kg organic manure, annual application of 100 g N, 50 g $P_2O_5$ and 50 g $K_2O$ per tree is advocated in ber plantations. Further raise in fertilizer dosage is recommended based on plant age and soil nutritional status of the area within. Aonla, custard apple and tamarind are all benefited from the application of 15–20 kg FYM per plant. 625 g N, 225 g $P_2O_5$ and 225 g $K_2O$ along with 50 kg FYM have been suggested for treatment to 5-year-old pomegranate trees at MPKV, Rahuri (Chander et al. 2012, 2013). Fertilization with 900 g N and 250 g K upgraded yield potential in 6- to 7-year-old fig trees spaced at 5 m × 5 m. Investigations on date palm at Abohar showed that annually application of 300–400 g N per tree resulted in increased fruit weight and number of fruit bunch.

Likewise, it was demonstrated that applying 50% of the recommended amount of nitrogen once in a month in pomegranate comes up with the optimum results (Srinivasa Rao et al. 2012). For the prospect of fertilizer conservation, trials were attempted to provide nutrients by means of fertigation through drip units in ber and pomegranate, which is reported to save fertilizer usage up to 25% unlike the conventional systems (Srinivasa Rao et al. 2012). As there is a growing demand for organic pomegranate, in order to strengthen its trade potential, inorganic fertilizers are highly replaced with organic manures. Several findings have shown that a good harvest of pomegranate can be obtained by fulfilling half of NPK need in form of vermicompost and rest half through synthetic fertilizers. Micronutrient insufficiencies are very common in semi-arid and dry soils.

Therefore, foliar application of fertilizers like zinc as ZnSO4 at 0.05–1.00% and boron as Borax at 0.05–1.00% to plants has given significant results in these deficit areas (Pareek and Sharma 1991). In a dry region, application of micronutrients FeSO4 at 0.50% + ZnSO4 at 0.50% + CuSO4 at 0.25% through foliar spray gave bumper harvest of quality fruits in kinnow mandarin. Foliar feeding has been proven to be the most effective method for micronutrient application for speedy recoupment of dietary prerequisites in plants. In semi-arid regions, foliar application of 0.5–1.0% ZnSO4 enhances the produce quality in ber cv. Seb (Singh and Vashishtha 1997).

### 18.8.9 Integrated Pest Management (IPM) Strategies

Pest and disease problems are observed to be less prevalent in dry regions than in humid regions, but the pest and disease species that have managed to survive through times in arid climates are more detrimental and often more difficult to manage. Furthermore, changes in climatic circumstances, such as a lengthy winter with cloudy overcast, are particularly conducive for pest and disease occurrence (Haldhar et al. 2018). If there is an increase in relative humidity in the environment over a lengthy period of time, there is a greater possibility of pest infestations. IPM tactics have been standardized in desert fruits and vegetable crops for timely management of pests and diseases. Thus, IPM approaches must be followed to decrease pesticide burden. Besides, soil solarization in summer months can destroy insect pupa residing inside. Perennial fruit trees should be given proper canopy design and field cleanliness to decrease pest/disease incidence in order to yield excellent fruits. In addition, commercially produced Cue-lure traps at 8–10/ha should be set to manage fruit flies efficiently (Haldhar et al. 2014).

### 18.8.10 Precision Farming

Precision farming has been quite successful in the USA and other well-developed foreign countries. While the management practices remain similar to an entire plot in conventional agricultural methodologies, precision farming techniques give emphasis on information technology with the use of site-specific soil, crop plant and other surrounding data to determine precise inputs needed for specific field sections (Meng et al. 2004). Numerous of these methodologies include advanced technical approaches such as GIS (geographic information system), remote sensing, satellites, etc. Accuracy in farming can specifically boost yields and also enhance moisture accessibility through increased relative penetration of precipitation in soil (Srinivasan et al. 2020). Precision agriculture may offer enormous opportunities to enhance potential of horticulture in developing nations in the future.

### 18.8.11 Post-harvest Management

Post-harvest losses account 20–40% occurring at different stages of grading, packing, storage, shipment and at last trading of both fresh and processed commodities. Value addition to perishable commodities is essential to obtain better price deal in the market. With the inadequacy of sufficient post-harvest and marketing infrastructures such as pre-cooling units, grading and packing sheds, brief and long-term cold storage provisions, refrigerated repository, storage and phytosanitary measures at air terminals, horticultural produce endures overwhelming post-harvest losses. Value addition alludes to the steps and series of approaches such as depiction of harvest index, pre-harvest treatment measures to diminish post-harvest misfortunes, harvesting methods to limit on-farm misfortunes, setting benchmarks for grading and packing for long-distance shipment, post-harvest treatments and storage facilities to enhance shelf life, processing methods to create more valuable products and waste utilization to manufacture usable by-products (More et al. 2012). Since plentiful of sunshine is available in dry locales, dehydration is commonly employed for vegetables and spices to prepare several value-added products. Many dehydrated commodities are available on the market, including sangri, methi leaves, coriander leaves and kachri. Brining, pickling, beverage preparation, making of preserves and other methods of value addition are being extensively used in several arid products. However, post-harvest management practices need to be commercialized in order to achieve better market prices for commodities.

## 18.9 Prospects of Dryland Horticulture

There is always a room for development of agricultural crops in dry regions, and it contains a parcel of guarantee for making an improvement in the country's cultivation situation. Besides, the region's poor occurrence of diseases/insects permits for the generation of high-quality seed and planting fabric for crop production (Hannachi et al. 2015). Commercial cultivation of Ber is done over 80,000 hectares of land, with an output of 0.9 Mt. within the country's arid and semi-arid regions. Pomegranate land coverage and production (1.14 Mt) are quickly rising in dry segments of the country, since there is a huge potential for its trade from arid and semi-arid zones. Pomegranate cultivation in Maharashtra alone has the area coverage of around 93,500 hectares productions. From India, pomegranate of worth Rs. 92 million is being exported to the Netherlands, Germany, Egypt, the Middle East, Bahrain, the United Kingdom, Kuwait and the United Arab Emirates (Centofanti et al. 2018).

Crops such as tamarind, fig and custard apple are moreover doing well in dryland situations. Fig is being grown on approximately 3000 hectares of land coming under Maharashtra and Karnataka. Custard apple is also cultivated in Maharashtra, Andhra Pradesh, Karnataka, Rajasthan and Tamil Nadu. Custard apple is naturally grown in the Arawali foothills, and its potential ought to be utilized. Aonla, being a potential medicinal fruit crop, is grown on over 55,000 hectares of land and 150 Mt. of fruit production each year. Date palm is the most fitting tree for hot dry arid zone, and it is raised in Haryana, Gujarat, Rajasthan and Punjab. Gujarat's land coverage under date palm is extended from 12,493 hectares in 2004–2005 to 16,688 hectares in 2009–2010 (Sharma et al. 2021). Date palm, on the other hand, is imported from Gulf countries due to the country's scanty yield. The tissue cultured plants of the cultivar Barhee have been planted on around 1000 acres of land in Gujarat's Kachchh range with an anticipated return of 17 crores from dates harvested (Muralidharan et al. 2008).

In western Rajasthan range, cultivars like Saggai, Medjool, Barhee, Zamli, Khalas, Khadrawy and Khunezi have been planted along with male cultivars Al-in-city and Ghanami in order to facilitate pollination. The tissue cultured date palm cultivars have been grown over around 250 hectares of land in Bikaner district of

Rajasthan. Farmers in Tamil Nadu have planted date palm over an area of 100 acres. Bael, being rich in nutritional and medicinal values, is also an important arid fruit crop grown commercially. India has been ranked to be the second-largest vegetable grower in the world (with a production of 125.88 Mt. from 5.77 Mha of area).

For vegetables, an extension in area coverage and production is achieved by 92.12 and 147.60%, respectively, whereas in major spices, increment in area and production by 6.98 and 83.73%, respectively, was noticed (Mallikarjunarao et al. 2015). According to the survey analysis report presented by the Department of Revenue in 2009–2010, around 32,000 hectares of area are coming under plantation crops in Rajasthan. The country's per capita vegetable consumption has reached a spike from 47 kg in 1984 to 76 kg in 2000, with a yearly increment rate of 2.9%. Several seed spices, such as fennel, fenugreek, nigella, coriander, dill, ajwain and cumin, are being cultivated on a huge scale and traded to earn hefty sum of foreign exchange (Rana et al. 2016), which is achieved as a result of the utilization of upgraded production technologies in dry regions.

Floriculture has a high potential in various regions of Rajasthan because of minimal disease and insect infestation and a high market demand for decoration and other applications. The potential of floriculture under hot dry circumstances is very significant in terms of seed and plant materials. Roses, marigolds, chrysanthemums and other flowers are now being cultivated in different districts of Rajasthan, namely, Kota, Sri Ganganagar, Jaipur, Udaipur and Ajmer. With the expansion of gardening, landscaping and floriculture in the state, as well as linked enterprises, there is a larger opportunity for tourism development (Singh et al. 2013).

## 18.10 Innovation in Technology Transfer

To attain dryland production stability, long-term, medium-term and short-term technologies must be integrated. The technologies that are created must be on a watershed basis, with the participation of the people. Methodologies for initiating and encouraging farmer engagement in dryland horticulture should be developed. Participatory rural evaluation and farmer group interaction to learn more about farmer perceptions will be used to understand a programme better and make it more valuable to dryland farmers (Rao and Ryan 2004 and Singh et al. 2004). The primary criterion will be grass root-level expansion. Despite the significant progress in agricultural experimentation and training, a large percentage of farmers are yet to be exposed to the new methodologies that have been produced (Singh et al. 2015).

In many regions of India's dry lands, non-governmental organizations tied with farmers have been proved effective. The self-help group concept is also attaining impulse in several Indian states. All of the measures combined together will aid in the development of dry lands for long-term productivity (Rao and Ryan 2004; Singh et al. 2004). With current research facilities, indigenous technical knowledge (ITKs) available in agricultural communities on numerous elements of farming might be developed. Farmers are more likely to accept refined ITKs (Rao and Ryan 2004; Singh et al. 2004). Other technological expertise like remote sensing also may be used to map dry lands on the basis of different parameters and then construct area-based programmes.

## 18.11 Opportunities in Arid Horticulture to Combat the Negative Impact of Climate Change

Exploring the unused potential of non-conventional regions such as desert and semi-arid zones has become necessary because expanding the horticulture on quality land is unlikely (Sharma et al. 2013). The arid region is bestowed with vast land resources, hardy natural biodiversity, surplus family laborers, expanded canal command areas, abundant solar and wind energy, high animal population and so on, all of which offer greater potential for successful wasteland utilization for commercial cultivation of fruits, vegetables, seed spices, medicinal and aromatic plants, ornamental plants, tuber crops and many others (Meena et al. 2022).

Because of its adaptation to varied biotic and abiotic stress conditions, the genetic diversity of desert ecosystems is extremely important. Perhaps it is a repository of 'genes' for stress tolerance and constitutes germplasm that must be gathered and stored to be used as donor in generating stress-tolerant/stress-resistant types or inducing tolerance in otherwise vulnerable but commercially valuable crops such as desert fruits and vegetables (Malik et al. 2018). Because desert fruits and vegetables are frequently cultivated in resource-poor environments, they possess hardiness against climate variations.

They feature a variety of xerophytic properties that aid in their tolerance toward the harsh environmental conditions of desert regions. The solid profound root framework of jamun, mateera, bael, wood apple, ber and aonla synchronizing their blossoming and fruiting (Saroj 2018) advancement with the season of water accessibility (ber, aonla, lasoda, etc.) and other xerophytic features like shedding of leaves in summer months (ber), meager leaves (ker), sharp cladode (cactus pear), plant portion with mucilaginous sap (bael, lasoda, ker, etc.), indented stomata and presence of fur/hair and waxy coating over leaf surface (phalsa, ber, lasoda fig, etc.), prickly character (ber, bael, karonda, ker, etc.) and specific or decreased absorption of cation ($Na^+$) and anions ($Cl^-$ and $SO_4^-$) are well-known characteristic highlights of dry vegetation for survival in unfavourable arid and semi-arid conditions (Saroj 2018). Ber, aonla, lasoda, karonda, bael, phalsa, wood apple, chironji and other dry and semi-arid fruits have enormous potential for mitigating the adverse impact of climatic aberrations. These fruits are nutritious and nutraceutically rich in several bioactive chemicals (Peterson et al. 2006). The demand for such fruits is increasing dramatically in both the domestic and foreign markets for processed products. These plants are ideal for agricultural diversification because they have unique resistant and tolerant features that allow them to tolerate climate changes globally (Saroj and Jatav 2019).

Furthermore, studying the physiological, biochemical and molecular underpinnings of adaptive behaviour of arid flora in severe hot and dry environments is a future focus topic in arid biodiversity research (Hannachi et al. 2015; Malhotra 2016). To perform high thorough research for creating resistant varieties of desert fruits and vegetables against diverse biotic and abiotic challenges, more focus should be placed on genomic and biotechnological interference for crop development (Sharma 2020). Genome editing with high-throughput technologies like CRISPR/ Cas9 might also be stressed for genetic improvement of desert fruits and vegetables for desired features (Kumar et al. 2019; Solankey et al. 2015).

Furthermore, the need should be addressed through the collection and evaluation of natural biodiversity of arid flora in order to develop a strong gene bank, including cryopreservation for conserving indigenous germplasm and the introduction of desired genotypes for breeding purposes in the face of a changing climate scenario (Akhtar et al. 2021). In situ conservation of neglected and underexploited species, land races of bael, jamun, khejri and others, should be encouraged to prevent extinction (Kumar et al. 2012). To maintain the livelihood of dry ecosystems, high yielding, nutrient-rich, short duration plants with desirable branching habit, early flowering, reduced inter-nodal length and appropriate for processing and export must be developed (Magray et al. 2014).

Exploration of heterosis breeding for desirable features such as earliness, preferred fruit size, prolonged harvesting, consistent quality and high commercial production must be prioritized (Martin 2019). Using molecular breeding technologies such as marker-assisted selection, different disease- and pest-resistant/tolerant varieties/ hybrids of desert fruits and vegetables should be created (MAS). Standardization of advanced manufacturing technology suitable to the different socioeconomic situations of the desert ecosystem is required (Portulaca 2022).

Focus should also be placed on the manufacture of high-quality seeds and planting material supply in order to boost productivity and quality (Magray et al. 2014). In order to meet climate changes, methods such as in situ orchard development, use of suitable rootstocks, effective canopy management, precision farming, IPM, INM and so on should be given careful consideration (Ramakrishna and Rao 2008). As high-quality irrigation water is scarce in dry regions, efforts should be made to preserve and improve water usage efficiency in order to harvest more crops per drop of water. Because livestock is an essential component of agriculture in arid regions, the only way to ensure the long-term growth of arid ecosystems is to diversify dry horticulture by including animal components such as poultry, fishing, beekeeping, forestry and so on (Choudhary and Saroj 2018).

Various fruit-based agroforestry systems have been standardized by including numerous compatible components that are practical, economically successful and ecologically beneficial. Adoption of such systems would not only reduce the chance of crop failure due to unfavourable weather conditions but will also be very cost-effective with many outputs. Inadequately trained human resources, suboptimal resource use, lack of quality seeds and planting materials, unorganized and scattered areas of fruit and vegetable production, high post-harvest losses and minimal farm level processing, poor marketing infrastructure, weak linkage with agro-based industries and other challenges that require strategic attention should be addressed by proper policy interventions at the grassroot level.

## 18.12 Conclusion

An enormous portion of the world's area is arid or semi-arid, and it faces a variety of challenges such as protracted drought, short and variable precipitation, high water and wind erosion, excessive heat and recurrent drought, bared and degraded soil and salinity problems in some low lands. Various restrictions, used collectively or separately, hampered soil productivity in these areas. Due to the limited resource availability, low productivity and a variety of unfavourable social and economic circumstances, most people in these places who rely on agriculture for a living are unable to withstand such issues. A lot of work has gone into developing technologies that are suitable with commercial arid horticulture crop production. To boost output, numerous varieties and agro-methods appropriate for dry regions have been developed. In semi-arid and arid areas, the horticulture production system must address these issues by boosting productivity, increasing revenue, reducing risk, preserving and efficiently exploiting available resources and mitigating and adapting to climatic irregularities.

Many researchers have strongly advocated for the use of suitable soil and water conservation methodologies, like mulching, bunding, conservation tillage and check dams that are relevant for the topography of land and rate of soil deterioration as well as the strength of climatic risk in that specific environment, to boost crop production and reduce barriers of crop production faced in semi-arid and arid geographic areas. In addition, cropping systems such as crop diversification, crop rotation and the use of severe climate tolerant crops, as well as integrating various agricultural systems such as livestock, agroforestry and field crops, all contribute significantly to minimizing unfavourable climatic impacts in arid regions. As a result, climatic and environmental risk factors in arid and semi-arid zones can be successfully mitigated by combining appropriate and well-suited production systems and/or implementing the best substitute production system with relevant soil and water management practices. However, several concerns must be addressed in order to further refine technology, better the socio-economic position of arid region peoples and establish a sustainable agro-horticulture system.

**Conflicts of Interest** The authors hereby declare no conflict of interest.

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# Part IV

# Crop Improvement and Pest Management

# 19

# Genetically Modified Crops and Crop Species Adapted to Global Warming in Dry Regions

Anamika Das, Manisha Mahanta, Biswajit Pramanik, and Shampa Purkayastha

## Abstract

The agriculture sector is largely dependent on weather. At present scenario, climate change is the biggest challenge for the agricultural community all over the world. Frequent droughts are a result of global warming, which severely affects the agricultural production in dry regions. Drought situation is further escalated by water stress caused by reducing water resources and pollution of water bodies. This drought situation adversely affects the crop production by reducing the water and nutrient use efficiency, which ultimately reduces the overall growth of the plant. To address this problem, many research programmes are oriented to develop abiotic stress-tolerant or drought-tolerant crops through genetic modification. The advancement of genetic engineering and plant transformation techniques plays a crucial role in the development of genetically modified crops. The various genetic engineering techniques being used for GMO development are transgenesis, cisgenesis, intragenesis and genome editing. The modification of a regulatory gene, which produces regulatory proteins that play a crucial role in the responses of plants to stress conditions, is more effective and widely used in the development of genetically modified crops for drought tolerance. Many efforts are being made to develop stress-tolerant crops by

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introducing heterologous genes from the organisms growing in extreme environmental conditions such as halophytes and thermophiles. There are some crop species in which stress-tolerant plants have been developed through genetic modification, e.g. rice, wheat, maize, mustard, soybean, sugarcane, tobacco, cotton, banana, potato, etc. For example, use of bacterial cold shock proteins (csp) has been reported in crops like *Arabidopsis*, rice and maize towards coping with the drought stress tolerance. Use of transcription factor, *Hahb-4* from sunflower, has been reported to induce drought tolerance in soybean and gene from *E. coli* and *Rhizobium meliloti* has been reported to induce stress tolerance in the case of sugarcane.

**Keywords**

Genetically modified · Abiotic stress · Genetic engineering · Transformation · Genome editing

## 19.1 Introduction

The global population is projected to reach around 9.6 billion in the next three decades. This will result in increased demand of food, resources and space. In addition to the increasing population, climate change is becoming a challenge for agricultural systems around the globe. The earth is projected to warm at least 2 degrees by 2050, which will be having a negative impact on the agricultural ecosystem (Bratspies 2016). Global warming, i.e. increased global mean surface temperature, wild fires, increase in frequency and severity of droughts, varied rainfall and frequent heavy rainfall leading to floods, is one of the consequences of climate change. The agriculture sector is largely dependent on climatic conditions. Therefore, it has become a big challenge for the agricultural community to provide food security for such a huge population with decreasing productivity of many crops due to climate change.

Around one-third of the global area comes under arid or semi-arid regions. In dry regions, where water level and annual precipitation are low, drought is the major reason for reduction in crop yield. Drought situation is further escalated by water stress caused by reducing water resources, pollution of water bodies and changing climatic conditions. Particularly, water availability throughout different growth stages of a crop is the most crucial component for optimum yield. The drought situation adversely affects the crop yield by reducing the water and nutrient use efficiency, which ultimately reduces the overall growth of the plant. Global warming demands incorporation of new traits in crop species to combat this stress. To address this problem, the scientific community is aggressively engaged in developing drought-tolerant varieties in many crop species (Liang 2016).

With the recent advances in biotechnological interventions, rapid development of efficient drought-tolerant crops has become possible by using genetic engineering and molecular biology than the conventional breeding and selection methods. The plants produced by the transfer of genes from another organism (transgenes) into their genome are called transgenic or genetically engineered plants. These are popularly known as genetically modified (GM) crops. A number of GM crops have been developed worldwide till date expressing various new traits such as disease resistance, insect resistance, herbicide tolerance, enhanced nutritional quality, etc. (Table 19.1). This chapter provides a brief outline of drought tolerant GM crops, techniques involved in development of GM crops and associated risks and legislations along with the future scope for researchers in this area.

## 19.2 Genetically Modified Crops in Dry Regions

Genetically modified crops are defined as crop plants developed by genetic engineering, i.e. insertion of foreign DNA into the host plant genome to develop plants expressing new or improved traits. To develop drought-tolerant GM crops, mechanisms of plant response to the environmental stresses have to be studied thoroughly. Regulated by a number of genes and signalling pathways, plant response to water stress is a very complicated process. The modification (up-regulation or down-regulation) of a regulatory gene, which produces regulatory proteins that play a crucial role in the responses of plants to stress conditions, is more effective and widely used in the development of genetically modified crops for drought tolerance (Liang 2016). An increased tolerance to stress was reported in rice and *Arabidopsis* by overexpression of some stress-inducible genes or transcription factors such as abscisic acid (ABA)-responsive element-binding factor (AREB), cup-shaped cotyledon (CUC), lack of apical meristem (NAM), etc. For instance, dehydration-responsive element-binding (DREB) proteins provide drought and salinity tolerance in *Arabidopsis* when overexpressed. In GM rice and tobacco were found tolerant to drought on overexpression of DREB1A gene. Similarly, overexpression of DREB2Aca also provides drought tolerance by inducing heat shock proteins (Nakashima and Suenaga 2017).

There are a number of reports on transferring genes related to drought tolerance from one species to another species, which upon expression in host plant species provide tolerance to drought stress (Table 19.2).

## 19.3 Techniques for GMO Development

Genetic engineering techniques employed for development of genetically modified crops play an important role in crop improvement either by improving the existing trait of the plant or by introducing a foreign gene into the plant genome. Based on the source of gene of interest, the techniques for developing GMO can be broadly classified as transgenesis, cisgenesis, intragenesis and genome editing. Transgenesis is the widely utilized technology for the development of transgenic plant with useful characteristics such as abiotic and biotic stress tolerances. However, the popularity and acceptance of transgenic crops is facing obstruction because of their

**Table 19.1** Development of various genetically modified crops around the globe

| Crop | Reported in (country) | Variety/ cultivars | Character(s) improved | Gene(s)/enzyme(s)*/protein (s)$^{\#}$ involved | Method (s) used | References |
|---|---|---|---|---|---|---|
| Wheat | Denmark | Bobwhite | Enhanced phytase activity | phyA | Transgenesis | Brinch-Pederson et al. (2000) |
| Potato | USA | Russet Burbank | Fungal (*Verticillium dahliae*) resistance | alfAFP | Transgenesis | Gao et al. (2000) |
| Wheat | Italy | Norstar | Improved freezing tolerance | CBF1, CBF2, CBF3 | Transgenesis | Jaglo et al. (2001) |
| Rye |  | Puma |  |  |  |  |
| Tomato | China | CL5915-93D4–1–0-3 | Improved chilling tolerance and oxidative stress | CBF1 | Transgenesis | Hsieh et al. (2002b) |
| Wheat | USA | Bobwhite | FHB resistance | TR1101 | Transgenesis | Okubara et al. (2002) |
| Potato | EU | Karnico | High amylopectin accumulation | GBSS | Intragenesis | de Vetten et al. (2003) |
| Potato | USA | NM | Late blight resistance | RB | Transgenesis | Song et al. (2003) |
| Potato | Canada | Desiree | Late blight and pink rot resistance | msrA3 | Transgenesis | Osusky et al. (2004) |
| Potato | USA | Ranger russet | Inhibiting black spot bruise | Ppo | Intragenesis | Rommens et al. (2004) |
| Potato | The Netherlands | ARF 87–601 | Late blight resistance | Rpi-blb2 | Transgenesis | van der Vossen et al. (2005) |
| Wheat | USA | Bobwhite | FHB resistance | AtNPR1 | Transgenesis | Makandar et al. (2006) |
| Potato | USA | White fleshed | Limiting cold-induced degradation of starch | R1 | Intragenesis | Rommens et al. (2006) |
| Wheat | Italy | Veery | FHB resistance | b-32 | Transgenesis | Balconi et al. (2007) |
| *Brassica napus* | USA | 26gA-8 | Increased NUE | AlaAT* | Transgenesis | Good et al. (2007) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Wheat | USA | Bobwhite | Improved FHB tolerance | α-1-purothionin, tlp-1 and β-1,3-glucanase | Transgenesis | Mackintosh et al. (2007) |
| Durum wheat | USA | Svevo | Improved baking quality | 1Dy10 | Cisgenesis | Gadaleta et al. (2008) |
| Potato | EU | NM | Late blight resistance | R | Cisgenesis | Haverkort et al. (2009) |
| Maize | USA | NM | Herbicide tolerance | IPK1 | Genome editing | Shukla et al. (2009) |
| Potato | USA | Russet ranger | Reduced acrylamide | StAs1 | Intragenesis | Chawla et al. (2012) |
| Barley | Denmark | Golden promise | Improved grain phytase activity | HvPAPhy_a | Cisgenesis | Holme et al. (2012) |
| Rice | USA | Kitaake | Development of disease-resistant variety | Os11N3 | Genome editing | Li et al. (2012) |
| Soybean | USA | Bert | Improved oil quality | FAD2-1A, FAD2-1B | Genome editing | Haun et al. (2014) |
| *Arabidopsis* | Germany | Columbia-0 | Directed mutagenesis | ADH1 | Genome editing | Schiml et al. (2014) |
| Wheat | China | Kenong 199 | Increased powdery mildew resistance | TaMLO-A1 | Genome editing | Wang et al. (2014) |
| Barley | UK | Golden promise | Crop improvement | HvPM19 | Genome editing | Lawrenson et al. (2015) |
| *B. oleracea* | | DH1012 | | BolC.GA4.a | | |
| Rice | China | Nipponbare | Improved storage tolerance | LOX3 | Genome editing | Ma et al. (2015) |
| Rice | China | Nipponbare | Improved fragrance | OsBADH2 | Genome editing | Shan et al. (2015) |
| Potato | USA | Ranger russet | Improved cold storage | VInv | Genome editing | Clasen et al. (2016) |

(continued)

**Table 19.1** (continued)

| Crop | Reported in (country) | Variety/ cultivars | Character(s) improved | Gene(s)/enzyme(s)*/protein (s)$^{\#}$ involved | Method (s) used | References |
|---|---|---|---|---|---|---|
| Soybean | China | Jack | Improved oil quality | GmPDS11, GmPDS18 | Genome editing | Du et al. (2016) |
| Soybean | China | Jack | Delayed flowering | GmFT2a | Genome editing | Cai et al. (2018) |
| Rice | China | Nipponbare | Improvement in grain filling | OsSWEET11 | Genome editing | Ma et al. (2017) |
| *Camelina sativa* | France | Céline | Reduced PUFA and increased oleic acid content | FAD2 | Genome editing | Morineau et al. (2017) |
| Rice | China | Nipponbare | Higher yield | DEP1, EP3, Gn1a, GS3, GW2 | Genome editing | Shen et al. (2017) |
| | | | Improved plant architecture | LPA1 | | |
| | | | Aroma | BADH2 | | |
| | | | Photoperiod insensitivity | Hd1 | | |
| Rice | China | Zhejing 88 | Improvement in yield | GS3, Gn1a | Genome editing | Shen et al. (2018) |
| Soybean | USA | NM | Higher oleic acid content | FAD2, FAD3 | Genome editing | Waltz (2018) |
| Rice | Columbia | Kitaake | Bacterial blight resistance | SWEET | Genome editing | Oliva et al. (2019) |
| Soybean | USA | Plenish | Higher oleic acid content | NM | Genome editing | Waltz (2019) |
| Rice | China | J809, L237, CNXJ | Improvement in yield | OsGS3, OsGW2, OsGn1a | Genome editing | Zhou et al. (2019) |
| Wheat | Argentina | IND-00412-7 | Increase in grain yield | HaHB4 | Transgenesis | González et al. (2020) |
| Soybean | | b10H | Improvement in yield performance | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Soybean | EU | GTS 40–3-2 | Herbicide (glyphosate) resistance | EPSPS* | Transgenesis | Gotte (2022) |
| Cotton | India | Bikaneri Nerma | Bollworm resistance | Cry1Ac | Transgenesis | Rao (2022) |

Abbreviations: *AlaAT* alanine aminotransferase, *alfAFP* alfalfa anti-fungal peptide, *EPSPS* 5-enolpyruvylshikimate-3-phosphate synthase, *EU* European Union, *NM* not mentioned, *VInv* vacuolar invertase gene

**Table 19.2** Development of various genetically modified drought-tolerant varieties/cultivars

| Crop | Reported in (country) | Variety/cultivars | Gene(s)/enzyme(s)*/protein(s)$^{\#}$ involved | Method (s) used | References |
|---|---|---|---|---|---|
| Potato | Germany | Desiree | StGCPRP | Transgenesis | Menke et al. (2000) |
| Wheat | Egypt | Hi-line | HVA1 | Transgenesis | Sivamani et al. (2000) |
| *B. napus* | Italy | Westar | CBF1, CBF2, CBF3 | Transgenesis | Jaglo et al. (2001) |
| Rice | Korea | PB-1 | TPSP | Transgenesis | Garg et al. (2002) |
| Tomato | China | CL5915-93D4–1–0-3 | CBF1 | Transgenesis | Hsieh et al. (2002a) |
| Rice | India | Pusa basmati 1 | HVA1 | Transgenesis | Rohila et al. (2002) |
| Tomato | China | CL5915–93D4–1-013 | CBF1 | Transgenesis | Lee et al. (2003) |
| Wheat | Mexico | MPB-bobwhite 26 | DREB1A | Transgenesis | Pellegrineschi et al. (2004) |
| Maize | USA | Hi II | NPK1 | Transgenesis | Shou et al. (2004) |
| Rice | Brazil | Taim 7 | APX3 | Transgenesis | Teixeira et al. (2006) |
| Wheat | Egypt | Hi-line | HVA1 | Transgenesis | Bahieldin et al. (2005) |
| Potato | Hungary | Desiree | DS2 | Transgenesis | Dóczi et al. (2005) |
| *B. napus* | Belgium | hpAtParp2 line | PARP | Transgenesis | De Block et al. (2005) |
| Rice | Korea | Nakdong | ABF3, ABF4 | Transgenesis | Oh et al. (2005) |
| *Arabidopsis* | USA | Columbia | ZAT10 | Transgenesis | Mittler et al. (2006) |
| Rice | China | IRAT109 | SNAC 1 | Transgenesis | Hu et al. (2006) |
| Soybean | Spain | Williams | PIP | Transgenesis | Porcel et al. (2006) |
| Lettuce |  | Romana |  |  |  |
| *Arabidopsis* | Japan | Columbia | DREB2A | Transgenesis | Sakuma et al. (2006) |
| *Arabidopsis* | USA | Columbia | SOS2 | Transgenesis | Batelli et al. (2007) |
| Peanut | India | JL 24 | DREB 1A | Transgenesis | Bhatnagar-Mathur et al. (2007) |
| Potato | Korea | NM | ABF, Rd22 | Transgenesis | Byun et al. (2007) |
| Potato | Korea | Superior | EREBP | Transgenesis | Lee et al. (2007) |

| | | | | | |
|---|---|---|---|---|---|
| Rice | Japan | Nipponbare | OsNAC6 | Transgenesis | Nakashima et al. (2007) |
| Rice | China | IRAT109 | LEA3 | Transgenesis | Xiao et al. (2007) |
| Tobacco | China | Wisconsin | VTE1 | Transgenesis | Liu et al. (2008) |
| *B. napus* | Canada | Westar | PtdIns-PLC2 | Transgenesis | Georges et al. (2009) |
| Tobacco | China | SR1 | LEA4 | Transgenesis | Liu et al. (2009) |
| Rice | Korea | Nakdong | AP37 | Transgenesis | Oh et al. (2009) |
| *B. napus* | Canada | DH12075 | BnFTA | Transgenesis | Wang et al. (2009) |
| Rice | China | Zhonghua 11 | LOS5, CBF3, NPK1, NHX1 | Transgenesis | Xiao et al. (2009) |
| Perennial ryegrass | NM | NM | Lpvp1 | Intragenesis | Bajaj et al. (2008) |
| Rice | Korea | Nipponbare | OsNAC10 | Transgenesis | Jeong et al. (2010) |
| *Arabidopsis* | UK | Columbia (Col-0), Wassilewskija (Ws) | ABI4 | Genome editing | Osakabe et al. (2010) |
| Rice | Korea | Nipponbare | OsNAC5 | Transgenesis | Jeong et al. (2010) |
| Cotton | USA | Coker 312 | AVP1 | Transgenesis | Pasapula et al. (2011) |
| Peanut | USA | New Mexico Valencia A | IPT | Transgenesis | Qin et al. (2011) |
| Maize | China | DH4866 | BetA, TsVP | Transgenesis | Wei et al. (2011) |
| Rice | Korea | Nipponbare | OsNAC9 | Transgenesis | Redillas et al. (2012) |
| Rice | China | Zhonghua 11 | BZIP46 | Transgenesis | Tang et al. (2012) |
| Maize | USA | Genuity® DroughtGard™ | CspB$^{\#}$ | Transgenesis | James (2013) |
| Soybean | China | Zhonghuang 20 | LOS5/ABA3 | Transgenesis | Li et al. (2013) |
| *B. napus* | China | Westar, Zhongshuang 9 | PLDα1 | Transgenesis | Lu et al. (2013a) |
| Maize | China | M-6 | LOS5 | Transgenesis | Lu et al. (2013b) |
| Wheat | China | Yangmai12 | NAC | Transgenesis | Saad et al. (2013) |
| Maize | USA | MON 87460 | Actin1 | Transgenesis | Sammons et al. (2014) |
| Maize | India | HKI532 | CuZn-SOD, Fe-SOD, Mn-SOD | Transgenesis | Shiriga et al. (2014) |
| *B. napus* | China | Zhongyou 821 (ov3 and ov11) | MAPK1 | Transgenesis | Weng et al. (2014) |

(continued)

**Table 19.2** (continued)

| Crop | Reported in (country) | Variety/cultivars | Gene(s)/enzyme(s)*/protein(s)$^{\#}$ involved | Method (s) used | References |
|---|---|---|---|---|---|
| *Arabidopsis* | Japan | CS67805, CS67806 | OST2 | Genome editing | Osakabe et al. (2016) |
| Soybean | China | EV | CYP82A3 | Transgenesis | Yan et al. (2016) |
| Finger millet | India | PR202 | MDAR | Transgenesis | Bartwal and Arora (2017) |
| Rice | India | Matta Triveni | COX1 | Transgenesis | Saakre et al. (2017) |
| Rice | China | Nipponbare | DRAP1 | Transgenesis | Huang et al. (2018) |
| *B. napus* | China | Westar | LEA3 and VOC | Transgenesis | Liang et al. (2019) |
| Sugarcane | Indonesia | NM | betA | Transgenesis | Kumar et al. (2020) |
| *B. napus* | China | Nannong 4 | NM | Transgenesis | Wang et al. (2020a) |
| *B. napus* | China | Zhongshuang 11 | MYC2 | Transgenesis | Wang et al. (2020b) |
| *B. napus* | China | Zhongshuang 11, NoWAX | BnKCS1–1, BnKCS1–2, BnCER1–2 | Transgenesis | Wang et al. (2020c) |
| Perennial ryegrass | New Zealand | Tolosa | VP1 | Cisgenesis | Templeton et al. (2021) |
| Soybean | Brazil | BRS 283 | DREB2A | Transgenesis | Marinho et al. (2022) |

*ABF* abscisic acid binding factor, *ABI4* ABA-insensitive 4, *AVP1 Arabidopsis* vacuolar H+ pyrophosphatase gene, *DS2* dehydration specific, *EREBP* ethylene-responsive element-binding protein, *FHB Fusarium* head blight, *IPT,* isopentenyltransferase, *KCR* 3-ketoacyl reductase, *KCS* 3-ketoacyl-CoA synthase, *LOX3* lipoxygenase, *MAPK1* MAP kinase 1, *NM* not mentioned, *NPK1* Nicotiana protein kinase 1; *NUE* nitrogen use efficiency, *PARP* poly (ADP-ribose) polymerase, *PLDα1* phospholipase Dα1, *PtdIns-PLC2* phosphatidylinositol-specific phospholipase C, *PUFA* polyunsaturated fatty acid, *Rd22* response to dehydration, *SOD* superoxide dismutase, *StGCPRP* guard cell proline rich protein, *tlp-1* thaumatin-like protein 1, *VP1* vacuolar pyrophosphatase 1 allergenicity, potential toxicity to humans and potential environmental risks concerned with it. These concerns have led to the development of alternate techniques like cisgenesis, intragenesis and genome editing in which plants' own gene or gene from a sexually compatible species is manipulated to achieve the desired trait in the plant.

### 19.3.1 Transgenesis

Transgenesis is defined as the process in which an exogenous gene, called a transgene, is introduced from one organism to another resulting in the expression of a new or enhanced characteristic in the recipient organism. The transgene can be from an unrelated plant or completely different species (Fig. 19.1a). It can be transferred naturally or by any of the genetic engineering techniques. In this process, first the gene of interest is extracted from the donor organism using restriction enzymes and then it is transferred to the recipient organism either directly or with the help of a vector. In the case of plants, it is achieved either through *Agrobaterium tumifaciens* as vector or through gene gun (a mechanical method where the DNA is shot into the plant cells). Plentiful reports are available on the development of transgenic plants with drought tolerance characteristic either enhanced or being transferred from an unrelated species (Table 19.2). Transfer of Nicotiana protein kinase 1 (NPK1) gene from tobacco into maize resulted in enhanced expression of heat shock proteins (HSPs), thereby protecting the photosynthetic mechanism of the plant from the damage caused by drought and maintaining the yield of the plant in stress conditions (Shou et al. 2004). microRNAs (miRNAs) are regulatory molecules which, in association with Argonaute proteins, recognize target mRNA sequence and function as negative transcriptional or translational regulators resulting in the expression of the characteristic. Transgenic barley has been reported by transferring miR827 from *Arabidopsis* that results in improved water use efficiency of barley, thereby improving the performance of barley in the drought condition (Ferdous et al. 2017). Genes encoding proteins that are involved in drought regulatory mechanisms can be incorporated in the plant's DNA to cope with the stress condition. These proteins can be transcription factors, protein kinases, enzymes related to osmoprotectants, etc. In rice, reports have been there showing the involvement of abscisic acid (ABA)-dependent and ABA-independent signalling pathways in response to abiotic stress tolerance. Transcription factors such as dehydration-responsive element binding, DREB-1 and DREB-2 are incorporated from *Arabidopsis* to rice resulting in the overexpression of these genes during stress conditions (Todaka et al. 2015). Incorporation of an isopentyl transferase (IPT) gene from *Agrobacterium* was also reported to enhance the drought tolerance trait in rice. These transgenic rice plants showed normal growth habit with optimum yield under drought condition (Peleg et al. 2011).

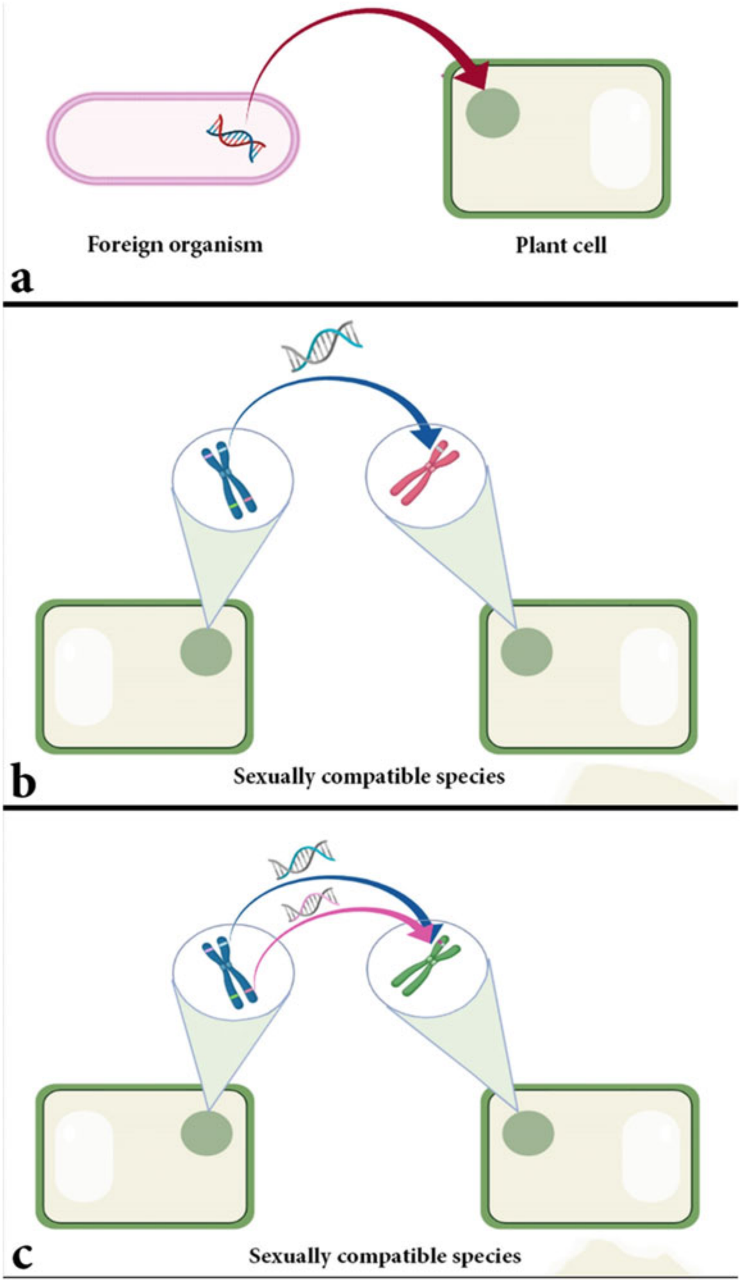

**Fig. 19.1** Development of GM crops. (**a**) Transgenesis. (**b**) Cisgenesis. (**c**) Intragenesis (created in Biorender.com) (https://biorender.com)

### 19.3.2 Cisgenesis

With the increasing work in the field of plant genome sequencing, isolation of plant genes responsible for specific traits from the crossable plant species has been possible. These genes from a crossable plant species are called 'cisgene'. It contains the introns, the exon along with its promoter and terminator sequence in normal sense orientation. As per Schouten et al. (2006), cisgenesis technique is an advanced breeding method in which a crop plant is modified genetically with one or more genes of interest isolated from the same plant species or a crossable donor plant (Fig. 19.1b). It can also be described as the transfer of only the specific genes from the gene pool of the crop species to a new variety without the transfer of the linked genes with the gene of interest (linkage drag). It differs from transgenesis in the way that the gene of interest is obtained from the crossable plant source rather than a non-plant-based organism or a sexually incompatible donor plant as in the case of transgenic plant development. A cisgenic transformation can be achieved using *Agrobacterium* as a vector for transferring the gene of interest to the recipient plant. Various biotic and abiotic stress resistances have been achieved in different crops through cisgenic transformation. For improving the drought tolerance of the crops to cope with the changing climate, the genes responsible for mechanisms that confer the plants to survive in stress condition can be transferred into the promising cultivar. This has been reported in a forage crop and ryegrass which was transformed using *Agrobaterium* as the vector and overexpression of the gene 'vacuolar pyrophosphatase 1' has been seen to impart high drought tolerance in the crop (Templeton et al. 2021).

### 19.3.3 Intragenesis

In intragenesis, asynthetic gene created in vitro by combining different elements as promoter, coding region, termination sequence of the same or different gene and introgressed into the same species or sexually cross compatible species (Fig. 19.1c). A new phenotype can be visualized in the existing species or it can be used to silence any gene by using RNA interference (RNAi). This gives the same effects as mutation breeding, which is not possible through conventional breeding. Therefore, in intragenesis a new trait is added to existing species without using any marker or vector. For example, in perennial ryegrass drought tolerance was achieved by overexpression of 'Lpvp1' gene (Holme et al. 2013). This technique also has certain limitations as it alters the proteins of the plant genome; hence, safety issues will be there. It shows position effect which changes the gene expression leading to phenotypic difference. Moreover, its construction is tedious and time consuming.

### 19.3.4 Genome Editing

It is also known as gene editing. An organism's DNA sequence can be changed via alteration of a sequence or sequence-specific modification of a specific base, at a particular location within the whole genome or knockout of the particular gene. By this method new trait can be expressed without having positional effect. To achieve this precise gene edition different technologies can be involved as CRISPR-Cas (clustered regularly interspaced short palindromic repeats-associated protein), ZFNs (zinc-finger nucleases) and TALENs (transcription activator-like effector nucleases) to knock out one or multiple genes (Kumar et al. 2020) (Fig. 19.2b). Genome editing is a powerful tool which mimics the DNA repair system in the cell. There are various sectors where these technologies can be successfully used for revolutionary change in different sectors of agriculture.

In 1985, ZFNs were introduced and TALENs were developed around 15 years later. But their designing, cytotoxic effects on non-target sequences are the limitations which have helped to develop as an alternative powerful tool CRISPR-Cas in 2012. The mechanism is similar to ZFNs and TALENs but in CRISPR, RNA guided the endonuclease to the target-specific site. It is robust, efficient, cost effective and easy to design, which makes it more popular than ZFNs and TALENs day by day. To make it more precise and to improve its applicability, different modifications such as base editing and primer editing were done with time for target-specific changes.

CRISPR can modify the target site, either by changing the sequence of DNA or creating some epigenetic changes, due to alternation in chromatin structure (Fig. 19.2a). It creates a double-stranded break at a specific site in host genome, which mimics the DNA repair machinery of cell and repair by non-homologous end joining (NHEJ), through which gene will be knocked out, or by homologous recombination (HR) to introduce changes in the DNA sequence at a desired region. CRISPR also helps to break linkage drag for introgression of a specific desirable gene only and stacking of desirable beneficial genes under the same background to create NILs. Moreover, CRISPR-Cas has the ability to edit the genome at different target sites without discriminating simultaneously. Transgenic crops are not accepted by society due to various reasons like ethical issues, cost efficiencies, etc., but with the help of CRISPR we can rid of these problems as here we don't introduce any gene from outside and hence it is highly acceptable. Along with these advantages of CRISPR-Cas, it has certain loopholes. It may cause off-target mutation due to the presence of identical target sites within a genome leading to cas9 endonuclease to detect the wrong sites.

The genome editing technology via any means has a great potential to minimize the devastating effects of the global warming on agriculture. For instance, drought-tolerant rice has been engineered by targeting its stomatal density (Yin et al. 2017). A decrease in stomatal density leads to an increase in the water use efficiency of rice in drought condition without affecting the yield. Also, in maize a promoter is knocked in before a gene to increase drought tolerance (Li et al. 2019), which leads to an increase in the yield in normal condition and gives better yield in stress

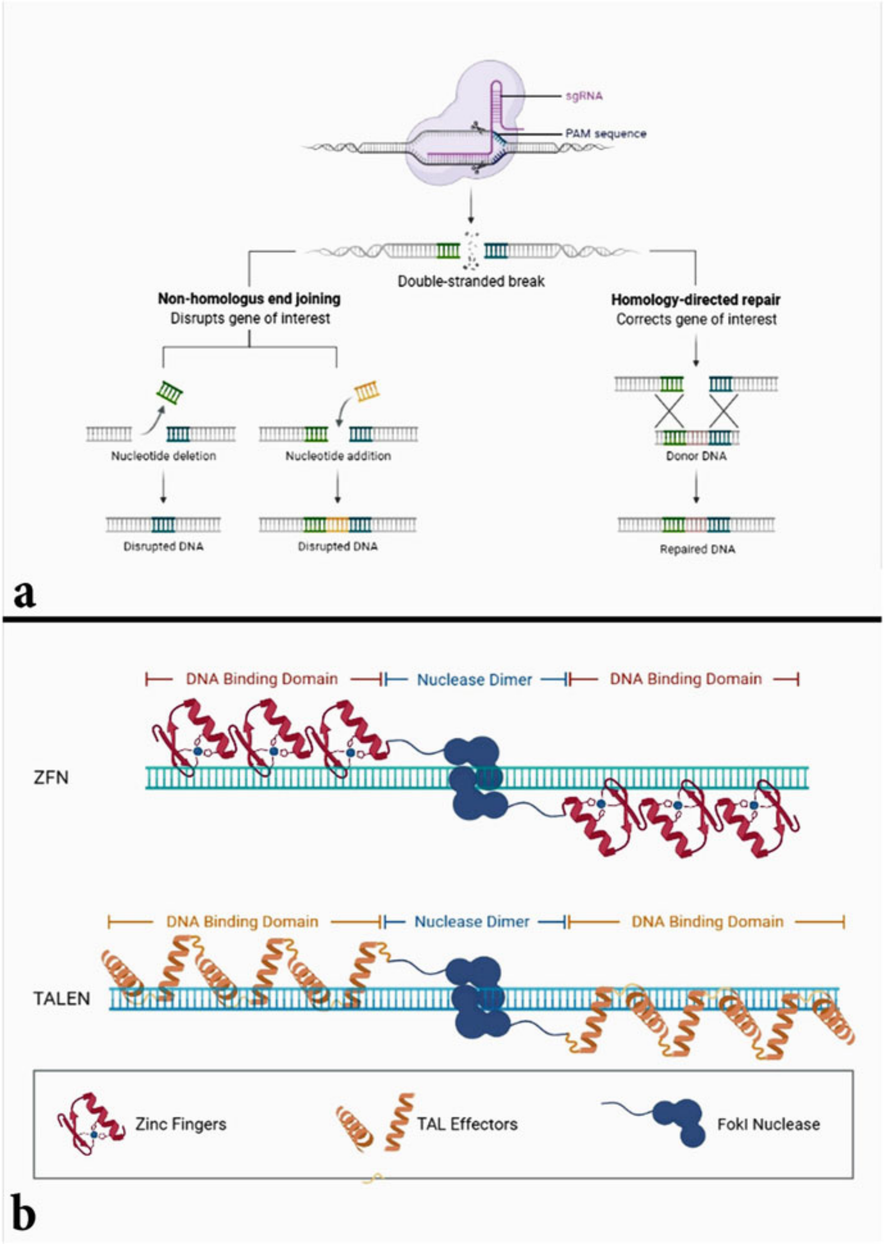

**Fig. 19.2** Diagram of genome editing for the development of GM crops. (**a**) CRISPR-Cas, (**b**) ZFNS and TALENs (Source: https://biorender.com)

condition. But the transforming efficiency of this technology is low in complex genome, i.e. cotton, *Brassica* and wheat. CRISPR-Cas gives a golden opportunity to control the gene expression (suppression or overexpression) done by base editing, knockout and knockin. Nuclear reorganization may have off-target effects, which increases the toxicity in the cell leading to safety concerns.

## 19.4 Safety Assessment of GMOs

With all the available GM crop development techniques, more or less safety concerns come in the picture. Therefore, safety assessment is an important step in developing a GMO and taking it towards commercialization. Safety assessment is done for the effect of GMOs or its products on any non-targeted organism and its environment. In general, a GMO safety assessment involves (a) characterization of the receiver parent; (b) characterization of donor organism from which the gene of interest is derived, the transformation process and the recombinant DNA sequence introduced; (c) safety assessment of introduced gene products (proteins and metabolites); and (d) food safety assessment of all the food products isolated from the GM plant (Liang 2016).

The major challenges with GM crops are safety concerns to human health (any kind of allergy or toxicity) and environment (horizontal transfer of transgenes), breakdown of resistance and non-targeted organisms being adversely affected (Kumar et al. 2020). Therefore, to assess the risks related to GM crops, there is the need of regulatory and legislative bodies for individual countries and internationally.

## 19.5 GMO Regulation and Legislations

The journey for improvement and commercialization of GM crops becomes no longer so easy now as compared to many different technological improvements and traits in different clinical fields. Huge debate goes on due to the fact that its advent and commercialization were confronted by many demonstrations and protests through NGOs, farmers and the public, and they got banned by many governments worldwide. USA, Canada and Japan had commercialized numerous meal and non-meal GMOs nicely among the general public in a large portion besides little sporadic competition to a few particular GM food crops. Recently, many Americans supported strongly for the labelling of food items which have been genetically changed. There is a robust competition of GM food crops in the UK and whole Europe; however, the UK Government is attempting strongly to persuade people about the protection of GMOs and its pressing want to feed approximately a thousand million hungry people in growing nations. GMOs are best allowed to apply for restrained non-meal functions in the UK and Europe. Latin American international locations especially Argentina and Brazil followed GMOs vigorously with little resistance from the overall population. Brazil and Argentina have recorded notably massive regions beneath GM crop cultivation since the last decade. About

10 Latin American international locations had accepted GM vegetation, out of overall 29 international locations in 2011, and approximately half of all growing GMO adopters are Latin Americans (Katovich 2012).

Debate regarding the GM food crops reached to growing global from evolved global after two decades of commercialization of the first GM crop in USA. The same groups, who had poised robust competition in Europe, are now preventing the GMOs to unfold in Africa. Few NGOs and nearby civil society and companies are resisting the opposition to GM banana that evolved in Uganda because of banana leaf wilt. However, many researchers have confirmed that genetically engineered crops are secure, but India remains to be watched for its first GM food crops to be commercialized. Deregulation on Bt brinjal has been placed on hold in 2010 by enforcing moratorium, whilst Bt cotton has been deregulated in 2002 in India. Idealistic beliefs, political reasons and lack of scientific knowledge are the main reasons for the resistance to GMOs in many developing countries, while psychological, emotional and political factors are some reasons for opposing the adoption of GMOs in developed countries. India has a comprehensive biosafety regulatory system in place and is pursuing aggressive research on genetically engineered crops. Seven biotechnology parks and incubation centres established by Department of Biotechnology (DBT), Govt. of India, has a great role in the research, development and commercialization of GM crops in different states.

There are differences in the provisions of GMO issuance between countries; some obvious differences are between the USA and Europe (Gaskell et al. 1999). Regulation changes in a country are given according to the use of genetic engineering products. Some countries have banned GMO issuance or restricted their usage and on the other hand, several nations have allowed them after going through different regulations. In 2016, 38 countries officially prohibit GMOs and 9 countries, namely, Algeria, Bhutan, Kenya, Madagascar, Peru, Russia, Venezuela and Zimbabwe, prohibit their imports. Most countries do not allow GMO farming but allow using GMOs for research. In spite of regulations, illegal discharge sometimes happened, due to the weakness of its implementation. The European Union (EU) is distinguished between the approval of culture in the EU and the approval of import and treatment (Purnhagen and Wesseler 2016). Although only a few GMOs have been approved in the EU, some GMOs have been approved for import and treatment (Wesseler and Purnhagen 2016).

## 19.6 Conclusion and Future Prospects

With population growth, cultivated land shrinkage and an increase in global warming, it is necessary to develop high-yielding plant varieties that are nutritious and resistant to a variety of environmental and biological stresses. Gene incorporation from one species to another or into the same species via traditional breeding is time consuming and labour intensive, leaving genetic engineering techniques as the most preferred methods for the development of genetically modified crops. GM crops with drought tolerance have contributed to the improved yields in dry regions all over the world. These crops can only be approved by regulators after rigorous safety assessments such as toxicity and allergenicity, but due to potential risks associated with the transgenes, there are some concerns about safety for the human health and environment. Due to these potential human health and environmental effects of GM crops, consumer acceptance is low in many countries. As transgenic crops possess safety concerns and are extensively utilized, other alternatives like cisgenesis and intragenesis can be explored for the development of GM crops.

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# Weed Management in Dryland Agriculture

# 20

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## Abstract

Drylands encompass more than 40% of the total land area and are home to 35% of the world's population. They have an aridity index ranging from 0.05 to 0.65. By 2050, the current world population of 7.7 billion people will have surpassed 9 billion. Contribution from dryland agriculture will be critical in meeting future food grain demand. Crop productivity in drylands is constrained by environmental, biotic, and socioeconomic factors. Weeds are the most significant biotic constraints in both developing and developed countries, competing with crops for key production factors such as moisture and nutrients. They cause severe yield losses ranging from 10% to 98% in dryland regions. Improved mechanical methods, broad-spectrum herbicides, bio-herbicides, biotechnology, allelopathy, and precision weed management tools must be used in conjunction with traditional practices to ensure efficient weed control. Hence, identification of

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economically viable weed management approaches is critical for increasing dryland productivity.

**Keywords**

Dryland · Crop productivity · Weed management · Resource conservation

## 20.1 Introduction

Drylands are an important component of the ecosystem, which also includes agricultural lands, grasslands, rangelands, forests, and degraded lands. They are critical for food security because they provide a living for millions of people around the world. Drylands cover 41% of total land surface (Fu et al. 2021), with the majority of area (72%) in developing countries inhabited by 90% of total drylands' population (Pravalie 2016). Thus, the development and prosperity of the dry regions hold the key to the development and prosperity of the country as a whole. Dryland agriculture is considered as a gamble with monsoon. They are characterized by low and erratic precipitation, marginal soils with poor soil fertility, limited water resources, and inefficient agronomic management practices resulting in partial or complete crop failure. Therefore, improving crop productivity is a major challenge in dryland agriculture.

In India, 69% of total geographical area and 57% of total cultivated area are under dryland regions inhabited by 43% of total population (Singh et al. 2018). They contribute 40% to the total food grain requirement and support 60% of livestock population of the country (Haileslassie and Craufard 2012). They account for a significant share of the area under major food and industrial crops – coarse cereals (85%), rice (42%), pulses (83%), oilseeds (70%), and cotton (65%) (CRIDA 2011). However, in dryland areas, the productivity of all of these crops is extremely low. Aside from extreme weather events, the use of unscientific cultivation practices, low-yielding traditional varieties, and improper or no input application are the major constraints causing low yields (Rao 2004). As a result, there is a need for improved dryland agricultural management practices to increase crop productivity by reducing crop failure (Koohafkan and Stewart 2008).

One of the most important management practices for increasing dryland crop productivity is effective weed control (Lee and Thierfelder 2017). Weeds compete with crops for soil moisture, nutrients, and other production factors, reducing dryland crop yields and quality (Umrani 1995). Among the major pests (insects, weeds, and diseases), weeds alone reduce crop yields to an extent of 10–98% in dryland regions (Ramamoorthy et al. 2004). The amount of yield loss varies depending on the crop, location, season, and other factors such as weed pressure, weed control practices, the cost of weed control technology, and the level of crop management practices (Rezene and Etagegnehu 1994; Das et al. 2021b). As a result, improved weed control practices and timely weed management are critical for increasing crop productivity in dryland areas (Ramakrishna and Tripathi 1995).

## 20.2 Attributes of Dryland Weeds

Weed species and weed composition in drylands vary with the climatic factors, soil, and agronomic management practices. Many dryland weed species have the capacity to adapt to severe moisture and nutrient stress during their growth cycle. The main characteristics of dryland weeds, i.e. short life cycle, waxy leaf coating, reduced leaf area, transpiration rate, and deep root system, enable them to survive under aberrant weather conditions. Weeds are classified as annuals, biennials, or perennials related to the life cycle. The majority of weeds in dryland areas are perennials and annuals, with only a small percentage being biennials (Rao 1983). They have extensive root system with thick, broad, and large leaves. Some weed species produce few leaves, temporarily halting shoot growth for a period of time, while the root system penetrates deeply into the soil. The presence of deep root system will enable them to extract water from deeper layers of soil profile. Further, the dryland weeds possess morphological adaptations like leaf twisting, curling, and folding as a water conservation mechanism to avoid heat stress and moisture stress. Drought avoidance and tolerance mechanisms are important strategies of dryland weeds for their drought adaptation (Chaves et al. 2003). Many of the grassy weeds in drylands have $C_4$ photosynthetic pathway which enables them to maintain photosynthetic activity with closed stomata, e.g. *Panicum* sp. (Lopes et al. 2011). During prolonged dry spells, some weed species go dormant and germinate when the environment is desirable for seedling development. Some of the dryland weed species propagate through underground tubers and remain viable even under extreme moisture stress and high temperature conditions of drylands. Weeds are therefore persistent in nature under harsh climatic conditions and severely compete with crop plants for essential production factors in dryland agriculture as a result of these specific characteristics. Some of the predominant dryland weeds are listed below:

Grasses: *Cynodon dactylon*, *Panicum repens*, *Dactyloctenium aegyptium*, *Andropogon contortus*, *Perotis indica*, *Cenchrus setigerus*.

Broadleaf weeds: *Acanthospermum hispidum*, *Achyranthes aspera*, *Amaranthus spinosus*, *Abutilon indicum*, *Aristolochia bracteata*, *Leucas aspera*, *Solanum elaeagnifolium*, *Borreria hispida*, *Borreria articularis*, *Tephrosia spinosa*, *Crotalaria burhia*, *Pluchea lanceolata*, *Celosia argentea*.

Sedges: *Cyperus rotundus and Fimbristylis miliacea*.

## 20.3 Factors Affecting Weed Emergence in Dryland Areas

In dryland regions, weed emergence, their distribution, and survival are affected by many climatic, edaphic, and biotic factors.

### 20.3.1 Climatic Factors

Soil moisture, temperature, and sunlight are the three prime factors determining the germination capacity and growth of weed seeds in dryland areas (Travlos et al. 2020). Light intensity, quality, and duration influence the germination, growth, and distribution of weeds. Tolerance to shading is one of the adaptations of weeds to persist. Seed dormancy is the major survival mechanism of weeds which is affected greatly by soil and atmospheric temperature (Rao 1983). Soil moisture affects the nature of weed flora (Wiese and Binning 1987). Weed species found in dry areas differ from those found in humid environments.

### 20.3.2 Edaphic Factors

Weed flora in dryland areas is influenced by soil temperature, pH, soil-water aeration, fertility status, and cropping systems. Some weeds, known as 'basophiles', thrive in alkali soils with pH levels ranging from 7.4 to 8.5. The best examples of basophiles are alkali grass (*Puccinellia* spp.) and quack grass (*Agropyron repens*) (Ramakrishna and Tripathi 1995), and some weeds grow well in acidic soils with a pH range of 4.5–6.5 and are referred to as 'acidophiles'. Acidophiles include *Digitaria sanguinalis*, *Borreria* spp., etc. Weeds can adapt and thrive in poor, marginal soils with low fertility. Thatch grass (*Imperata cylindrica* Beauv.) thrives in both low and high fertility soils. *Commelina benghalensis* L., on the other hand, thrives in both moist and dry soil conditions (Ramakrishna et al. 1991).

### 20.3.3 Biotic Factors

Plants and animals affect the weed flora in a variety of ways, both directly and indirectly, by affecting their persistence. Crop management practices and cropping systems influence weed growth and development (Ramakrishna and Tripathi 1995). Tillage and intercultivation operations alter the soil surface, affecting weed germination and weed flora shift (Sauer et al. 1996).

## 20.4 Critical Period of Crop-Weed Competition

Weeds compete for soil moisture, nutrients, sunlight, and space with crops, reducing crop yields and quality. The critical period of crop-weed competition is described as the time during crop growth when weeds must be controlled to avoid yield loss to the greatest extent possible (Knezevic et al. 2002). It is essential for planning appropriate weed management strategies and precise timing of weed control measures (Rao et al. 2010). Many factors affect the critical period of weed competition such as type of crop and weed, their competitive ability, time of weed emergence, weed density and the availability of resources, and environmental conditions. Dryland crops are

**Table 20.1** Critical period of crop-weed competition in various crops grown on dryland

| SI no. | Crop | Critical period |
|---|---|---|
| 1 | Maize | 20–30 DAS |
| 2 | Sesamum | 15–45 DAS |
| 3 | Pearl millet | 15–30 |
| 4 | Ground nut | 3–8 weeks of sowing |
| 5 | Greengram | 20–30 |
| 6 | Blackgram | 10–40 |
| 7 | Soybean | 30–45 |
| 8 | Wheat | 30–50 |
| 9 | Rapeseed and mustard | 15–40 |
| 10 | Pigeonpea | 6–8 weeks after sowing |
| 11 | Chickpea | 17–49 days after emergence |
| 12 | Lentil | 7.7 to 9.3 weeks after emergence |

*DAS* days after sowing
(Source: Singh et al. 2018)

mostly grown with conserved soil moisture. Thus, effective weed management is essential to avoid moisture stress at critical growth stages. Knowing the critical period of weed control and the factors influencing it is critical for making appropriate decisions on weed control timing and herbicide efficiency (Kumar et al. 2015). The critical period of crop-weed competition for various crops under dryland agriculture is presented in Table 20.1.

## 20.5 Weed Shift Vulnerability in Drylands

The shift in weed flora is an important aspect of agriculture in dryland regions of the world that are transitioning from extensive to intensive cultivation. Weed flora varies from locality to locality, region to region, and continent to continent. Baisure (*Pluchea lanceolata*), kandiari (*Carthamus oxyacantha*), prickly pear (*Opuntia* spp.), and Kans (*Saccharum spontaneum* L.) are noxious weeds that infest 70% of India's dryland areas (Ramakrishna and Tripathi 1995). Weeds such as mesquite (*Prosopis juliflora*), cedar, giant crab grass, and Johnson grass, for example, were common in US rangelands but not as severe in Asian and African regions (Ramamoorthy et al. 2004).

Plant distribution across regions and continents, persistent herbicide applications, frequent tillage operations, and cropping system changes can all cause weed flora shifts (Sen et al. 1981). If the ecological conditions are favourable, exotic weeds can become extremely invasive in a new area. They may become dominant in new regions in a short period of time, successfully displacing earlier established species. One such troublesome weed is *Eichhornia crassipes* (water hyacinth), which was introduced to India from South America around 1890 and has since spread throughout the country, primarily infesting the Ganga and Brahmaputra deltaic regions (Joshi 1974). Due to the significantly higher evapotranspiration rates of weed-covered water surfaces compared to open water surfaces, it obstructs water bodies and irrigation systems, as well as interfering directly with rice growth and indirectly with the growth of a wide range of crops. *Phalaris minor* L. is a Mediterranean weed that has become a prominent weed in Mexico. In recent decades, its presence in wheat- and maize-growing areas in Northern India has increased dramatically (Ramamoorthy et al. 2004). Mani et al. (1975) described *Parthenium hysterophorus* L. as a wasteland weed. It is a native of Central and North America that was introduced to India in 1956 and has since spread around the country, occupying over ten million ha of urban waste land, village grazing lands, and many dryland crop lands (Parihar and Kanodia 1987). The introduction of herbicides and their application is a good example of a change in agronomic methods that might lead to adverse modifications in weed flora. According to Singh (1995), *Cyperus rotundus* has become increasingly problematic in most dryland locations in recent years. Since the development of selective herbicides, more easily controlled weeds have been eradicated from the mixed plant population, leaving plenty of room for weed shifts. Persistent application of pre-emergence pendimethalin to a rainfed rice-pulse cropping system eliminated all total annual weeds and major weeds such as *Echinochloa colona* L. and *Cleome viscosa* L., allowing for a severe infestation of *Cyperus rotundus* L.

Changes in cropping systems can also result in the change of weed flora composition for a variety of reasons. Changes in agronomic practices may also make it easier for imported weed seeds to spread and cause severe infestations (Hooda and Malik 1980). In India, the wild oat (*Avena fatua* L.) problem became acute with the introduction of new high-yielding wheat cultivars (Rao 1983). In several regions, this weed has lowered the production of new wheat cultivars. Sen (1981) found that when rice-wheat rotation became prevalent with the introduction of canal irrigation, *Phalaris minor* infestation was at its peak. The weed species *Phalaris minor* and *Avena fatua* have spread rapidly due to their morphological similarity with wheat plants up to flowering, tremendous reproductive potential, seed shedding 2 or 3 weeks before wheat harvest, and seed dormancy (Ramkrishna and Tripathi 1995).

## 20.6 Economic Losses Caused by Weeds in India and Other Countries

Crop production is hampered by biotic and abiotic factors, as well as socioeconomic and crop management concerns (Ghersa 2013). Maintaining production levels necessitates the creation of new ideas and methods for mitigating the negative effects of these factors. Weeds are the most detrimental biotic constraint to agricultural productivity, as well as impacting agrobiodiversity and natural water bodies in both developing and developed countries (Chauhan et al. 2017). They also have an indirect impact on crop productivity by competing for resources (such as sunlight, water, nutrients, and space), hiding crop pests, interfering with water management, and reducing yield and quality (Zimdahl 2010). Weed-related crop yield losses are affected by a number of factors, including weed emergence time, weed density, weed type, and crop, among others (Chauhan et al. 2012). Weeds, if left unchecked, can result in a 100% yield loss. Weeds reduced crop productivity in India by 22.7% during the winter and 36.5% during the summer and rainy seasons, according to Bhan et al. (1999). Weed-related economic losses in India have been estimated to range between INR 20 and INR 28 billion (Sahoo and Saraswat 1988; Sachan 1989). Weeds cost the Indian economy INR 1050 billion per year, according to another study (Varshney and Prasad Babu 2008).

Weeds alone are estimated to cause a total annual economic loss of approximately USD 11 billion in 10 major crops across 18 states of India (Gharde et al. 2018). Rice suffered a 14% actual average yield loss in transplanted conditions and a 21% yield loss in direct-seeded conditions, but due to its high production, it is considered the most economically affected crop in India compared to the other crops considered here. According to Yaduraju (2006), if weed losses are assumed to be 10%, the economic losses are expected to be more than USD 13 billion, resulting in a loss of approximately 25 million tonnes of total food grains in India.

Weeds are held responsible for a 13.2% decrease in the production of the world's eight most important food and cash crops (Oerke 2006). Weeds are estimated to cost Australian grain growers AUD 3.3 billion per year (Llewellyn et al. 2016). Weeds reduced grain yield by 2.7 million tonnes in Australia. According to Oliveira et al. (2014), in Brazil, insect pests induce an average annual yield reduction of 7.7%, leading to a loss of approximately 25 million tonnes of food, fibre, and biofuels. The overall annual economic losses were anticipated to be around USD 17.7 billion. Weeds cost the United States USD 33 billion in crop production losses each year (Pimentel et al. 2005). Soltani et al. (2016) also reported a 50% average yield loss in corn, equating to a loss of 148 million tonnes of corn worth approximately USD 26.7 billion in the United States and Canada each year. Weeds cost more than USD 100 billion in crop losses each year around the world, and the use of herbicides for weed control costs an additional USD 25 billion (Gharde et al. 2018).

## 20.7 Dryland Weed Management Strategies

Numerous weed management practices, such as preventive, cultural, mechanical, biological, biotechnological, and chemical methods, are effective in controlling weeds in dryland agriculture, either alone or in combination.

### 20.7.1 Preventive Methods

The first and most important method of weed management is prevention, which includes all measures taken to prevent weed entry and spread at the local, regional, and national levels. The old adage 'one year's seeding makes seven years' weeding' refers to the vigour and spread of weed seeds. Thus, measures that arrests the spread of weeds include production of weed-free seeds, cleaning of weed-infested seed, using well-decomposed manure, clean farm machineries, cleaning irrigation channels and farm bunds, and proper quarantine and regulation of contaminated crop seed. Major weeds contaminated with cereal crops were weedy rice in rice, *Chenopodium album* and *Phalaris minor* in wheat, annual ryegrass in barley, and wild oats (*Avena* spp.) in oat. The main foreign seeds in pulse crops were narrowleaf clover (*Trifolium angustifolium* L.), wireweed (*Polygonum aviculare* L.), Medicago spp., and vetch (*Vicia sativa* L.) (Azmi and Karim 2008, Niknam et al. 2002). The weeds contaminated with oilseed crops are *Argemone mexicana* with rapeseed and mustard, *Ipomoea* spp., *Ambrosia* spp., and *Xanthium strumarium* with soybean. Use of such contaminated seeds results in entry and spread of weeds from an infested area to a clean area. Therefore, careful selection of seed production fields ensuring that crop-associated weeds are not established and use of weed-free crop seed are critical to produce weed-free crop seed. Use of agricultural equipments during different farm operations disperses the weed seeds from one place to another. Combine harvesters transport a significant weed seed load between fields, dispersing *Bromus* seeds 1.9 m behind and up to 20 m ahead of the point of introduction (Howard et al. 1991). According to Shirtliffe and Entz (2005), wild oat seeds were dispersed 145 m beyond the field boundary. Cleaning harvesters, seed cleaners, hay balers, and other farm implements between fields reduce dispersal potential and allow for future weed management efforts. Livestock also transports weeds to new areas because the seeds they ingest survive passage through the digestive tract, potentially resulting in the dispersal of weed species (*Rumex obtusifolius*) (Beskow et al. 2006). Furthermore, the seeds and fruits of many weed species, such as *Lasiurus sindicus*, *Cenchrus biflorus*, *Xanthium strumarium*, *Tribulus terrestris*, *Achyranthes aspera*, and others, contain spines, thorns, and hooks that adhere to the skin and fur of farm livestock and wild animals, resulting in weed seed dispersal from one location to another (Singh et al. 2018). As a result, limiting the entry of farm livestock and wild animals can help to prevent weed seed spread into new areas. Weed species such as *Parthenium hysterophorus*, *Lantana camera*, *Phalaris minor*, and others were introduced to India via contaminated seed or agricultural products imported from other countries (Yadav and Malik 2005). Strict quarantine and legal measures are required to prevent the interstate and international movement of noxious weeds. Farmers must inspect their fields on a regular basis and remove rogue new weeds as soon as they appear. Weeds along roadsides, railroad tracks, and waste areas should also be addressed through weed legislation. As a result, prevention should be regarded as the most important strategy for preventing the introduction of new weed species into weed-free areas.

### 20.7.2 Cultural Methods

Cultural methods reduce weed competition and improve crop competitive ability. Cultural practices are the use of appropriate crop cultivars, planting pattern, fertilization and irrigation plan, crop rotation, cover crops, intercropping, stale seedbed, and soil solarization. Crop cultivars with early vigour and quick canopy closure, combined with proper irrigation and fertilizer scheduling, are capable of competing with weeds. Crop rotation prevents or reduces the accumulation of large populations of weeds that are common to a particular crop. Crop rotation is an effective method of controlling crop-associated and crop-bound weeds such as *Avena fatua* in wheat. Weeds like *Cyperus rotundus* can be effectively controlled by inclusion of low-land rice into crop rotation. Fast-growing cover crops can exert a direct weed suppression effect either as a pure crop or as a living mulch mainly through resource competition. Moonen and Barberi (2004) discovered a 25% reduction in total weed seed bank density 7 years after introducing a rye cover crop versus a non-cover cropped corn system. Many examples of increased weed suppression and yield achieved through intercropping in Indian conditions involve cereal-pulse combinations. When compared to sole crops, pearl millet intercropped with cluster bean and moth bean and maize intercropped with cowpea resulted in lower weed density (Kiroriwal and Yadav 2013; Selvakumar and Sundari 2006). Stale seedbed formation is successful when the majority of non-dormant weeds in the top 6 cm of the soil profile emerge and are killed prior to crop planting (Boyd et al. 2006). Preventive and cultural methods must supplement direct approaches based on herbicides and mechanical methods such as cultivation to achieve better weed control.

### 20.7.3 Thermal Methods

The use of fire, burning, hot water, steam, and freezing to control weeds is based on the thermal control of weeds, which allows for quick weed removal while leaving no chemical residues in the soil or water. Furthermore, thermal methods are weed-selective; don’t disturb the soil, and thus don’t bring buried seeds to the surface. The basic understanding behind these thermal weed management approaches is to kill plants/weeds by heating them to a point where their cellular membranes disintegrate. Thermal weed control methods are divided into two types based on their mode of action: (1) direct heating (hot water, steaming, flame, infrared weeders, or hot air) and (2) indirect heating (electrocution, micro-waves, laser radiation, or UV-light). Cryogenic techniques are a third thermal weed control strategy (Rask and Kristoffersen 2007). In this method, soil solarization, weed flaming, and weed steaming have been discussed.

### 20.7.4 Soil Solarization

Solarization is a chemical-free weed control method that involves breaking weed seed dormancy, solar scorching of emerged weeds, and direct heat killing of weed seeds. In comparison to unmulched soil, soil solarization raises soil temperature by 8–12 °C (Yaduraju 2006, Singh et al. 2018). This pre-plant method entails covering the soil surface with a cover, such as black or transparent plastic, to trap solar energy and encourage an increase in soil temperature for 4–6 weeks throughout the summer, when the soil receives the most sunlight. Soil absorbs the sun’s energy and raises its temperature to a point where many soil-borne diseases are killed. Solarization has been said to be successful in managing weeds in corn by up to 98% (Ahmad et al. 1996), whereas crop damage due to weeds alone has been observed to be 90% in non-solarized control plots (Elmore et al. 1997). Annual weeds such as *Poa annua*, *Ageratum* spp., *Amaranthus* sp., *Echinochloa* sp., *Imperata cylindrica*, *Portulaca oleracea*, *Digitaria* sp., *Portulaca* sp., *Amaranthus retroflexus*, *Setaria* sp., and many others have been successfully controlled by solarization (Benlioglu et al. 2005).

### 20.7.5 Weed Flaming

Weed flaming could be another thermal weed control technique that has been used effectively for horticultural crops; it has also been used efficiently for maize production in Europe and the United States (Melander et al. 2013). Flaming is the process of subjecting plant tissues to flames produced by a burner that is typically powered by propane (Stepanovic et al. 2015). Flaming is the most popular thermal method used in organic (Kang 2001) and conventional agricultural systems, and it uses propane gas burners or, more recently, renewable alternatives like hydrogen to achieve combustion temperatures of up to 1900 °C, quickly elevating the temperature of exposed plant tissues (Knezevic et al. 2016). Flaming is used to control weeds rather than burning plant tissues. Throughout the 1960s, flaming was widely used to control weeds in cotton, maize, sorghum, soybean, potato, and other crops in the United States (Knezevic et al. 2016). Pesticide leakage into surface and groundwater, as well as pesticide residues in drinking water and food, has brought awareness and compelled herbicide use restrictions in recent years. As a result of these factors, weed flaming has reawakened interest in organic agricultural production systems due to its less expensive and effective weed management. Flaming is most successful in the early stages of growth of tall and broad-leaved weeds, and it has been demonstrated to be less efficient in the control of grassy and prostrate weeds (Ascard 1995). When compared to other weed control methods, flame weeding offers various advantages. It is less expensive than hand weeding (Fennimore et al. 2010; Ulloa et al. 2010). Crop root injury is unlikely, especially when heat-tolerant agronomic crops such as maize, cotton, and sugarcane are used, or when the flame is directed to the crop's base to suppress intra-row weeds (Cisneros and Zandstra 2008). It is compatible with zero tillage techniques, making it excellent for fields with erosion issues (Hatcher and Melander 2003). However, there is a danger of crop damage, human injury, or the method's ineffectiveness on particular species of weeds. Safety is a major concern when it comes to flame weeding, especially with tractor-mounted machines and large amounts of crop residue in the field.

### 20.7.6 Weed Steaming

Steam controls emergent weeds and weed seeds in the soil seed bank in this thermal method (Melander et al. 2013). Foliar steam application, also known as steam control of emerging weeds, is accomplished by applying steam to the weed foliage at a high enough temperature to destroy plant membranes. Steam, rather than hot water, has been claimed to be a faster, more effective, and longer-lasting weed management technique, especially when weeds are growing on relatively hard surfaces (Rask and Kristoffersen 2007). Weed seeds, as well as soil-borne pests and viruses, are destroyed by soil steaming in particular (Dumas et al. 1998; Peruzzi et al. 2012). Soil steaming reduces the weed seed bank more than the stale seedbed technique by killing weed seeds buried up to 20 cm deep (Barberi et al. 2009).

The effectiveness of thermal methods such as soil solarization, weed flaming, and weed steaming has been experimented by various researchers, though they are not widely implemented in India. While all three strategies have the potential to be effective for weed suppression in dryland areas, more research and more cost-effective options are required before they can be recommended to farmers.

### 20.7.7 Mechanical Methods

Hoeing, tillage, and harrowing are all mechanical weed control methods (Kewat 2014). Weeds are killed in three ways under this method: (1) cutting, (2) uprooting, and (3) burial (Chicouene 2007). Tillage during seedbed preparation prevents weeds from germinating by burying weed seeds deeply in the soil. Tillage not only destroys weed seedlings but also loosens soil and improves tilth which is important to crop yield. Animal-drawn cultivation tools and tractor-driven machines reduced the labour and time required for soil tillage and weed control. In wide row spaced crops like sugarcane, cotton, and orchards, the inter-row weeds are controlled by small farm implements like mini-weeders, power tillers, and minitractor-drawn rotavator (Deshmukh and Tiwari 2011). Weeds in the row have a significant impact on yield and are difficult to control. Harrowing is a long-established method for mechanical intra-row weed control in deeply sown crops such as beans and peas that treats the entire area – both crop and weed plants (Van der Weide et al. 2008). Hoeing-ridging provided excellent control of both inter- and intra-row weeds and had the potential to prevent the development of uncontrolled weeds in maize, sunflower, and soybean. Several tools, including finger weeders, brush weeders, torsion weeders, mini ridgers, and computer-vision-guided hoes, are effective at controlling intra-row weeds (Van der Weide et al. 2008). Summer ploughing twice at 45 days interval reduced the population of *Cyperus rotundus*, *Cyperus difformis*, and *Fimbristylis littoralis* in the succeeding crops (Bahadur et al. 2015). The combination of mechanical weed control and other non-chemical weed management methods may aid in achieving long-term weed control.

### 20.7.8 Chemical Methods

In the present time, our food security is threatened by a rapidly growing population (Babu et al. 2020; Meena et al. 2021). As a result, increased agricultural production is required (Babu et al. 2020). But crop losses due to various pests, i.e. insects, weeds, nematodes, diseases, etc., are a major concern. Chemical weed control measures are critical in the agriculture sector (Yadav et al. 2021). Herbicides can be used to control weeds as well as to eliminate crop-weed interference. Herbicides, for example, offer the benefit of weed control at the right time. These are an essential component of a successful integrated weed management system (Moss 2019). Herbicide consumption is currently higher than that of insecticides, fungicides, and other pesticides worldwide (Jabran et al. 2015). Herbicide consumption has increased in developing countries like India over the last few decades due to shortage of labour. Timely crop planting operations are hampered by labour scarcity and rising labour costs (Ghosh et al. 2021b). It offers cost-effective weed control while also increasing productivity (De et al. 2014). Herbicide application can also aid in the conservation of moisture in dryland agriculture by limiting weed population (Gandy et al. 2015). Millets are a dryland cereal crop that is severely weed-infested. Application of atrazine at 500 g/ha effectively suppresses weeds and boosts productivity while providing high net returns (Peterson and Westfall 2004). Application of imazethapyr (0.1 kg/ha) 15 days after sowing of crop can control weeds in pigeonpea, mungbean, and other pulse crops (Tiwana et al. 2002; Singh et al. 2018). Herbicides such as atrazine, pendimethalin, alachlor, fluchloralin, imazethapyr, FOP group herbicides, and oxyfluorfen are used in dryland agriculture to manage weeds. The chemical structures of the most commonly used herbicides in dryland agriculture are depicted in Fig. 20.1.

### 20.7.9 Biological Methods

Biological weed control entails the use of living organisms such as insects, nematodes, bacteria, pathogens, or fungi to impact the health of the weed or reduce weed populations. The use of insects that feed on weeds dates back to the nineteenth century. *Dactylopius ceylonicus* (Green) was brought to India to be used in the production of cochineal dye. This introduction resulted in *Opuntia monacantha* biological control rather than dye production. Following its release in India, the insect was introduced to South Africa and Australia, where it proved effective in weed control (Van Wilgen et al. 2013). *Zygogramma bicolorata* was used to control *Parthenium hysterophorus* in India, which was a key development in biological weed control (Kumar and Ray 2011). Water hyacinth (Ray et al. 2009) and water fern have been the primary targets of biological weed management initiatives in Southeast Asia (Table 20.2).

Plant pathogenic fungi (*Alternaria*, *Penicillium*, and *Fusarium*) and bacteria produce various metabolites including alkaloids, glycosides, peptides, phenolics, and terpenoids. These compounds can be exploited for their use as weed control and offer best alternatives to chemical herbicides. Finding pathogens of major weeds with parasitism levels high enough to be specific but low enough to be lethal when used in inundative inoculations is essential in the development of pathogens as mycoherbicides. A few Indian companies claim to have successfully formulated a

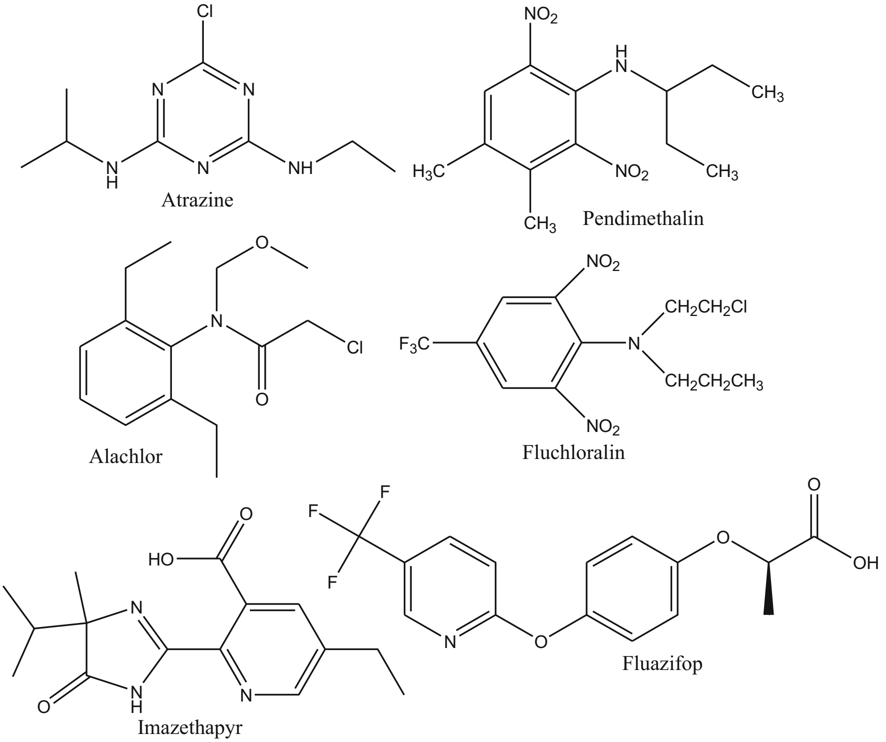


**Fig. 20.1** Chemical structures of most commonly used herbicides

**Table 20.2** List of weeds controlled by insects

| Weed species | Insect | | |
|---|---|---|---|
| Species | Family | Species | Order, family |
| *Salvinia molesta* | Salviniaceae | *Cyrtobagous salviniae* | Coleoptera, Curculionidae |
| *Alternanthera philoxeroides* | Amaranthaceae | *Agasicles hygrophila* | Chrysomelidae, Coleoptera |
| *Opuntia* spp. | Cactaceae | *Dactylopius ceylonicus*<br>*D. opuntiae*<br>*D. tomentosus* | Hemiptera, Dactylopiidae |
| *Lantana camara* | Verbenaceae | *Ophiomyia lantanae*<br>*Crocidosema lantana* | Diptera, Agromyzidae<br>Lepidoptera, Tortricidae |
| *Parthenium hysterophorus* | Asteraceae | *Zygogramma bicolorata* | Chrysomelidae, Coleoptera |
| *Cyperus rotundus* | Cyperaceae | *Bactra verutana* | Lepidoptera, Tortricidae |
| *Orobanche* spp. | Orobanchaceae | *Phytomyza orobanche* | Diptera, Agromyzidae |

product from fungi isolates against *Parthenium* and water hyacinth, but large-scale field application is still awaited (Sharma et al. 2020). Due to increasing environmental and anthropogenic problems, the biological approach, as an integral part of integrated and sustainable weed control approaches, is playing an increasingly important role and forethought.

### 20.7.10 Biotechnological Methods

Biotechnology approaches to weed management have gained popularity in several parts of the world in recent years, particularly in the United States. Herbicide-resistant crops, improved bio-herbicides, transgenic allelopathy in crops, and weed characterization using molecular systematics are all examples of biotechnological tools that can aid in weed management (Datta and Pilli 2019).

### 20.7.11 Herbicide-Resistant Crops

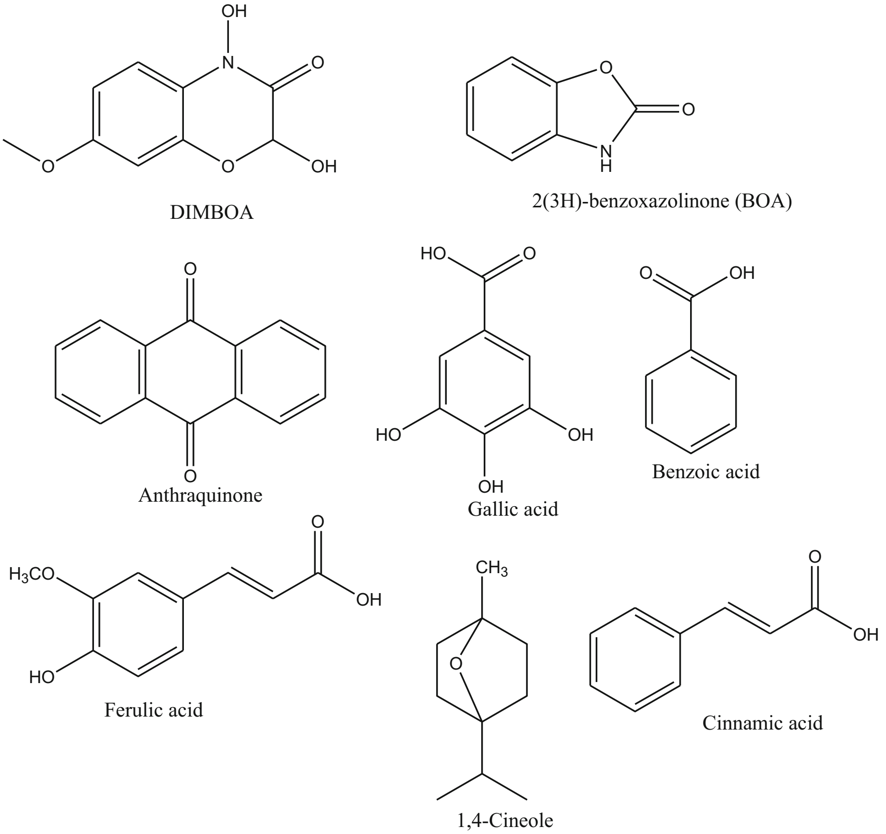
Herbicide resistance refers to a population of plants' capacity to endure a significantly higher dose of a specific herbicide than the wild type of that plant. Herbicide-resistant crop can be developed through i) traditional plant breeding and ii) biotechnology. However, the latter techniques are more predominant than the older one in recent years. The techniques include a) in vitro mutant selection at the cell or tissue level (Radin and Carlson 1978) somatic hybridization (Binding et al. 1982) microspore and seed mutagenesis (Pinthus et al. 1972), and d) plant transformation or transfer of cloned genes into susceptible plants (Caplan et al. 1983; Doring, 1985; Crossway et al. 1986; Potrykus et al. 1985). The direct transfer of cloned genes into sensitive plant cells is currently regarded as the most powerful method of genetically manipulating crop tolerance to herbicides. Herbicide-resistant crops account for the vast majority of genetically modified (GM) crops (83%) (Beckie et al. 2006). Herbicide-resistant crops' introduction and widespread acceptance is primarily due to its capability to efficiently manage weeds. Biotechnology has been used to develop herbicide-resistant crops that are resistant to glyphosate, glufosinate, bromoxynil, imidazolinone, and dicamba (Gealy et al. 2003; Givens et al. 2009). Cotton, corn, canola, rice, sugar beet, alfalfa, brassica, and soybean are examples of herbicide-resistant crops (Gealy et al. 2003) that have revolutionized weed management in the United States (Givens et al. 2009), Canada (Beckie et al. 2006), Australia (Duke and Powles 2009), and other countries. Herbicide-resistant crops benefit from higher crop yield and decreased crop injury owing to a broader spectrum of weed control. However, whether or not herbicide resistance in weeds is causing a shift in weed flora, caution should be exercised. Integrative approaches based on stacked gene crops and rotational herbicide use could provide efficient weed control in a diverse array of cropping regimes in the coming years.

### 20.7.12 Bio-Herbicides

Weeds can be controlled with living bio-control agents in the same way that herbicides are. However, due to a number of shortcomings when compared to chemical herbicides, bio-control has not been widely used for weed management in agronomic and horticultural crops (Datta and Pilli 2019). A bio-control agent is a living organism or biological entity that is used to reduce the population of weeds. Parasites, predators (insects, mites), pathogens (fungi, bacterium, virus), and botanical agents are only a few examples. Mycoherbicides are fungus-based weed-killing pathogens. For example, *Alternaria alternata* is used to control the weed water hyacinth. Bio-herbicides have the advantage of being highly selective for the target organism and being biodegradable by nature. Biotechnology is currently being used to enhance host specificity and virulence in bio-control agents, particularly bio-herbicides.

### 20.7.13 Allelopathy

Allelopathy is a process that produces allelochemicals, which are biochemicals. It describes the inhibitory/disruptive effects of one plant species on another in terms of germination, growth, survival, development, and metabolism (Latif et al. 2017). Zhao et al. (2019) described the allelopathic properties of *Eucalyptus*. It was discovered that the allelopathic properties of *Eucalyptus* planation resulted in poor vegetation/crop growth. Terpenoids and phenolic acids were discovered to be responsible for the allelopathic properties. Application of allelopathic weed or crop plant residue is used as mulches or cultivation in a rotational sequence (Farooq et al. 2013). Allelopathic effects on agricultural production have two primary goals: to reduce chemical load and to provide effective methods for environmental sustainability (Macias et al. 2003; Han et al. 2013). Allelochemicals are a good alternative to synthetic herbicides because they do not have residual problem (Bhadoria 2011). Herbicidal weed control in conventional agriculture is not only costly, it is also environmentally harmful (Cheema et al. 2004). Allelopathic crops are used in agriculture as mulches, cover crops, rotational crops, and also green manure (Cheema et al. 2004; Khanh et al. 2005; Farooq et al. 2013; Haider et al. 2015). When used as topsoil cover, allelopathic plants have been found to be a promising option for weed management in dryland agriculture (Wang et al. 2013). Allelopathic effects have improved crop productivity and pest control in an environmentally friendly manner, as well as the development of novel pesticides based on allelochemicals, which has piqued the interest of allelopathic researchers. Plant root exudates have been found to contain several compounds such as butyric, terpenoids, flavonoids, steroids, alkaloids, phenolic acids, coumarin, fatty acids, anthraquinone, and other complex quinones. Figure 20.2 depicts the chemical structures of some allelochemical compounds. The suppression effect in crops is primarily due to competitive interactions among them (Sanjerehei et al. 2011). But, allelopathic plants can sometimes cause problems such as autotoxicity, vegetative propagation



DIMBOA

2(3H)-benzoxazolinone (BOA)

Anthraquinone

Gallic acid

Benzoic acid

Ferulic acid

1,4-Cineole

Cinnamic acid

**Fig. 20.2** Chemical structures of some allelochemicals

failure, increased crop-weed interference, increased pest susceptibility, reduced nutrient uptake, nitrification, and soil sicknesses (Cheng and Cheng 2015).

### 20.7.14 Development of Transgenic Allelopathy in Crops

Biotechnology has expanded the scope of herbicide technology. Transgene technology has been used to produce herbicide-resistant crops, which has had a major impact on the herbicide market. The same technology has the potential to improve crop competitiveness against weeds by improving competitive traits or making the crop more allelopathic. Allelopathy can be used in weed management in three ways: (1) as a winter cover crop that provides allelopathic residue, (2) as a living mulch during the cropping season, and (3) as an isolated compound from an allelopathic plant applied as a herbicide (Datta and Pilli 2019). Methods for creating transgenic allelopathy in crops are as follows:

The First Approach: Pools of mRNAs expressing allelopathic traits are extracted from tissues and compared, and an expressed sequence tag (EST) database is formed. Following that, allelochemical-producing gene is introduced into the desired crop plant. Allelochemical biosynthesis is then regulated by increasing the release rate or extending the release time.

Second Method: Using genetic engineering, allelopathic traits can be transferred between cultivars of the same species or between species. As a result, crop varieties with increased allelopathy are created, either by increasing gene expression of existing allelochemical pathways or by inserting genes for the synthesis of new allelochemicals. Duke et al. (2001) used molecular biology and transgenic techniques to increase the content of sorgoleone in sorghum, which is a strong phytotoxin for many weeds.

### 20.7.15 Characterization of Weeds Using Molecular Systematics

Molecular systematics is the use of molecular genetics to investigate the evolution of links between individuals and species. We need molecular systematics because morphological data has limitations, such as a limited number of characteristics, misunderstanding of characteristic changes, classical taxonomy being difficult, and phenotypic vs. genotypic differences being not obvious (Datta and Pilli 2019). Weed biotypes are identified, and molecular markers are used to investigate genetic links between biotypes. This is useful for understanding how weeds adapt and spread, as well as determining the best old-world areas to search for natural enemies for biological control programmes.

### 20.7.16 Improved Resource Conservation Technologies

The key to developing sustainable farming systems in dryland areas is efficient management of the natural resource base. A variety of resource conservation technologies have been proposed to boost productivity and sustainability in these areas.

#### 20.7.16.1 Conservation Agriculture (CA)

CA entails no or minimal mechanical soil disturbance, biomass mulch soil cover, and crop species diversification (Kassam et al. 2019). Zero tillage (ZT) systems concentrate seeds near the surface of the soil, which creates favourable conditions for germination; however, they are also more susceptible to mortality because of variations in weather and predation (Nichols et al. 2015). Crop rotation and residue cover could be effective weed management techniques (Baghel et al. 2020). Crop residues act as physical barriers, preventing both light penetration and the emergence of weed seedlings. Crop residues may restrict weed seedling emergence, lag emergence, and allow the crop to gain an early vigour advantage over weeds when present evenly and densely under CA (Chauhan et al. 2012). Crop rotation affects weeds through allelopathy and changes in crop management and resource demands (Nichols et al. 2015). Residue cover forms an insulator between the soil and the atmosphere, reducing evaporative losses and maintaining humidity. CA can also enhance soil quality by increasing soil microbial activity, nutrient availability, soil moisture retention, and use efficiency (Six et al. 2002; Hobbs et al. 2008; Ghosh et al. 2019; Das et al. 2021a). Crop yields under CA frequently increase in water-stressed situations (Farooq et al. 2011; Pittelkow et al. 2015).

#### 20.7.16.2 Bed Planting

Raised permanent beds aid in the retention of rainfall and have been shown to increase crop yield and water productivity in sorghum (Jones and Clark 1987; Govaerts et al. 2005). Drilling dry rice seeding in a furrow-irrigated raised-bed planting system (FIRBS) uses less water than transplanting rice on puddled soil (Vethaiya et al. 2003). The FIRBS helps in saving nitrogen fertilizer, seed, and water and is being encouraged in areas where water is scarce (Sharma and Singh 2002; Singh et al. 2006). Permanent raised beds preserve a permanent soil cover, contributing to increased rainwater collection and conservation (Govaerts et al. 2005). Over conventional ZT with flat planting, permanent raised-bed planting saves irrigation water and weeding costs (Das et al. 2014). The furrows function as drainage routes during heavy rains and serve to retain rainwater during dry spells (Astatke et al. 2002). In maize, a permanent broad bed with residue using 75% of the recommended nitrogen dose resulted in 34% less weed density than conventional tillage (Ghosh et al. 2021a). When wheat is sown in FIRBS or in lines under a flatbed system, mechanical weed control can be used efficiently (Chhokar et al. 2012). Mechanical weeding, FIRBS, and other methods can also help to reduce weed competition (Chauhan et al. 2003).

#### 20.7.16.3 Crop Diversification

Crop diversification is influenced by a variety of factors such as land suitability, water availability, and regional, seasonal, and temporal market conditions (Nishan 2014). Crop diversification is also influenced by increased profitability and production stability. Soil moisture may be insufficient to support two crops in dryland areas with rainfall of 625–700 mm. Intercropping systems can then be used to increase cropping intensity over a single crop in this case. Intercropping in widely spaced crops can reduce weed infestation while increasing overall productivity. Crops with different botanical relationships should be changed for weeds, pests, and disease control (Gangwar et al. 2016). Change in soil moisture and fertility conditions, residue cover, micro-topography, and other soil properties occur as crops vary within a rotation sequence, influencing weed distribution and dynamics by destabilizing their environment (Liebman et al. 2001). Crop diversification reduces weed density by interfering with weed seed germination and growth. Furthermore, diverse farming systems are more resistant to climate change than monoculture systems and produce higher crop yields (Sharma et al. 2021). Crop diversification has emerged as an important strategy for farmers seeking to stabilize their income flow (Behera et al. 2007).

#### 20.7.16.4 Brown Manuring

Most dryland soils in the country are low in organic carbon owing to the quick oxidation reaction in these regions (Rao et al. 2006). Green manure crops contribute significantly to soil health and crop productivity. They suppress weeds, reduce herbicide use and irrigation water, conserve moisture, improve soil C content, and boost farm profitability (Das et al. 2020). In brown manuring practice, green manure crops such as *Sesbania*/*Crotalaria* are grown with a crop for a short period of time (25–30 days) before being killed with a post-emergence herbicide (Tanwar et al. 2010). Rice, maize, pearl millet, sorghum, and other crops can benefit from this practice. However, apart from weed control, brown manuring has numerous advantages such as delaying the development of herbicide resistance, reducing disease organism populations, improving soil quality parameters, controlling soil erosion, and leading to increased soil fertility (Behera et al. 2019). According to Oyeogbe et al. (2017), weed management through brown manuring increased maize grain yield by up to 10% when compared to unweeded control. Behera et al. (2018) determined that a 1:1 mixture of *Sesbania bispinosa* and *Crotalaria juncea* (12.5 + 12.5 kg/ha) and 2,4-D at 0.5 kg/ha at 25 DAS would be the best brown manuring practice in maize for increased productivity while improving weed control efficiency.

#### 20.7.16.5 Sub-Surface Drip Irrigation

Subsurface drip irrigation systems have been adopted and adapted in a wide range of geographical regions for different crops grown in various soil types and climates (Lamm 2002). Grattan et al. (1988) found less weed biomass in tomato fields irrigated with subsurface drip as opposed to furrow or sprinkler irrigation methods in Davis, California. They reported that subsurface drip irrigation without herbicides could be effective in weed control while also reducing chemical reliance. Weed germination and growth are significantly reduced because the SDI system is buried, particularly in the area between rows (Ayars et al. 2015). Subsurface drip irrigation may restrict wetting of the soil surface, inhibiting weed germination and growth better than conventional tillage and herbicide applications (Sutton et al. 2006). In semi-arid areas, subsurface drip irrigation combined with no tillage could lay the cornerstone of a promising alternative weed management system (Shrestha et al. 2007).

#### 20.7.16.6 Precision Weed Management

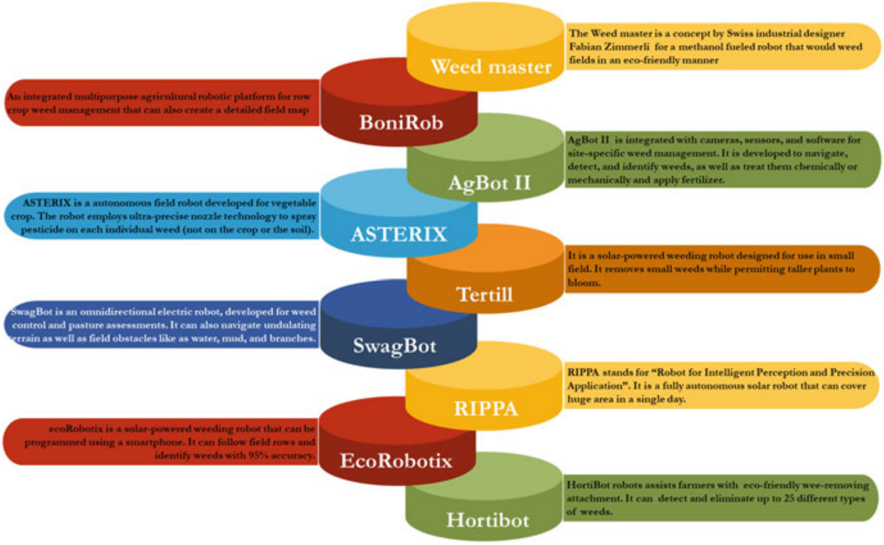
Precision farming, also referred to as site-specific crop management, is a concept that involves sensing or observing crop spatial and temporal variability and responding with management actions (Monteiro and Santos 2022). Precision agriculture and improved weed management have the capability to help close the yield gap (Young et al. 2014). The continued increase in the number of herbicide-resistant biotypes emphasizes the lesson that weed control technology must constantly advance in order to keep up with weed evolution and adaptation (Westwood et al., 2018). Integrated weed management, in conjunction with the use of unmanned aerial vehicles, enables site-specific weed management, which is a highly efficient and environmentally friendly methodology (Esposito et al. 2021). Weed control robots are being developed at a rapid pace, particularly for vegetable crops and organic agriculture (Korres et al. 2019). It may also lower costs, the risk of crop failure, leftover herbicide residue, and the impact on the environment (Partel et al. 2019).

### 20.7.16.7 Agricultural Robotics for Weed Management

An effective weed control strategy must be robust as well as adaptable. Robustness in weed control is referred to as efficient control of weeds despite the variety in field circumstances and a weed control method is said to be adaptable if it can change its strategies based on the variability in the weed dynamics and environmental conditions. Traditional weed control methods, like as chemical and mechanical weed control, are generally effective with farmers' experience and management skills, but their adaptability is limited (Steward et al. 2019). Agricultural robotics has the potential to provide much more adaptive weed control mechanisms, even down to the plant scale, from small to large. Integration of artificial intelligence (AI) with agricultural robotics transforms the future of agricultural robotics towards smart and precision farming. However, introducing AI and robotics technologies to weed management, presents several difficulties that need to be addressed to increase the efficiency, robustness, and adaptability of robotic weed management.

The primary goal of agricultural robotics is to replace human labour with field robots that can perform tasks more precisely and uniformly at a lower cost and with greater efficiency (Bloch et al. 2018). Weed control and precise spraying with robots not only reduce the labour dependency but also reduce the wastage of herbicides. Precision spraying with robots for weed management has yielded satisfactory results and reduced herbicide consumption by 5–10% when compared to conventional spraying (Midtiby et al. 2011). Over the last 20 years, various potential weed robot technologies have been proposed and executed, albeit they are still not fully commercialized. Some of the well-known robots that are efficiently involved in various types of weed management activities are Weedmaster, BoniRob (Ruckelshausen et al. 2009), AgBot II (Bawden et al. 2014), ASTERIX (Utstumo, 2018), Tertill (MacKean et al. 2021), Hortibot (Jorgensen et al. 2007), SwagBot (Eiffert et al. 2020), RIPPA (Bogue, 2016), EcoRobotix (Steward et al. 2019), etc. The abovementioned robots have been discussed below (Fig. 20.3).

Precision agriculture has benefited greatly from the use of weed management robots. In developed countries, applications of these robots have grown exponentially, while in developing countries, they have yet to be triggered. Unlike in the industrial example, weed control robots are still in the prototype stage, and practical implementation is extremely challenging. To operate efficiently in real-world conditions, weed control robots should be accustomed to varied planting practices and weather conditions (Shamshiri et al. 2018). Various technologies such as artificial intelligence, machine vision, image processing, and sensors may be integrated into weed control robots, providing optimism for its application, but must overcome the difficulty in unstructured and diverse environments of agricultural fields (Kushwaha et al. 2016; Yeasin et al. 2021).



The Weed master is a concept by Swiss industrial designer Fabian Zimmerli for a methanol fueled robot that would weed fields in an eco-friendly manner

An integrated multipurpose agricultural robotic platform for row crop weed management that can also create a detailed field map

AgBot II is integrated with cameras, sensors, and software for site-specific weed management. It is developed to navigate, detect, and identify weeds, as well as treat them chemically or mechanically and apply fertilizer.

ASTERIX is a autonomous field robot developed for vegetable crop. The robot employs ultra-precise nozzle technology to spray pesticide on each individual weed (not on the crop or the soil).

It is a solar-powered weeding robot designed for use in small field. It removes small weeds while permitting taller plants to bloom.

SwagBot is an omnidirectional electric robot, developed for weed control and pasture assessments. It can also navigate undulating errain as well as field obstacles like as water, mud, and branches.

RIPPA stands for "Robot for Intelligent Perception and Precision Application". It is a fully autonomous solar robot that can cover huge area in a single day.

ecoRobotix is a solar-powered weeding robot that can be programmed using a smartphone. It can follow field rows and identify weeds with 95% accuracy.

HortiBot robots assists farmers with eco-friendly wee-removing attachment. It can detect and eliminate up to 25 different types of weeds.

**Fig. 20.3** Popular agricultural robots for weed management

### 20.7.16.8 Integrated Weed Management

Weeds pose a significant threat to crop growth and are responsible for one-third of crop production losses (Meena et al. 2016). As discussed in this chapter, several weed control measures are available to control weeds, but weed diversity and herbicide-resistant weeds are evolving as a result of overreliance on herbicides due to labour shortage (Chauhan et al. 2017). None of the single weed management methods can eradicate weeds completely. Therefore, an integrated approach with different weed management methods is needed to lower weed populations to levels below an economic threshold. In this context, integrated weed management (IWM) assumes greater importance. It manages weed populations through efficient, dependable, and feasible management strategies that are both economically sound and environmentally friendly in terms of improving and sustaining crop productivity (Sharma et al. 2013). The IWM system entails the use of well-adopted high-yielding crop cultivars that resist weed competition, the combination of best agronomic practices, timely inter-culture operations, sowing practices, optimum plant populations, use of crops that form a good canopy cover over weeds, precision placement/timing of fertilizer application, and judicious irrigation water use. To create a holistic approach both pre- and post-herbicides along with the good agricultural practices that reduce weed population and increase weed control use efficiency should be developed (Meena et al. 2019). The results reported by Bhargavi et al. (2016) revealed that application of oxyfluorfen at 100 g$\mathrm{ha}^{-1}$ as pre-emergence and a hand weeding at 20 days after transplanting resulted in effective weed suppression and high yield in finger millet. Tillage practices are also an important pillar of IWM, particularly in the presence of perennial weeds (Brandsaeter et al. 2011).

Mouldboard, chisel, disc harrow, and power tiller ploughs are examples of tillage practices that can be used to support IWM (Brandsaeter et al. 2011). IWM also includes biological weed control and the development of weed-suppressive crop varieties, both of which are possible given ongoing advances in understanding plant-pathogen and plant-plant interactions. Predators, pathogens, and other plant competitors of weeds are used in biological weed control to kill or suppress many agricultural weeds. Crop diversification and modified cropping systems allow for a diversification of weed management strategies that will affect the weed species in a different way (Liebman et al. 2001). Agricultural robotics could also be an important component in IWM. Considering the diversity of weed problems and agroecosystems, no single weed control method provides the desired level of efficency under all situations. Effective IWM should combine preventive, cultural, mechanical and biological weed control methods in an effective, economical and ecological manner. Therefore, adoption of IWM will increase the weed control efficiency and play a crucial role in the development of future sustainable agricultural practices.

## 20.8 Conclusion

Weeds are ubiquitous, and their adaptability is determined by their wide range of ecological amplitude. Weeds are one of the most significant barriers to improving dryland crop productivity and resource use efficiency. Weed management in dryland areas can be accomplished through a variety of methods, including preventive, cultural, mechanical, biological, biotechnological, and chemical methods. Due to labour shortages in many areas of the country, herbicides are becoming increasingly important for weed management. Their uncontrolled use, on the other hand, has risen herbicide-resistant weeds including the risks of herbicide residues. For effective weed management, research on low-dose and high-potency molecules with controlled release formulations is critical. Herbicide wastage and residue hazards will be greatly reduced with site-specific weed management based on remote sensing technology. Sensor technology used in precision weed management has the potential to significantly lower herbicide consumption. Biotechnological approaches, such as the use of bio-herbicides and efficient strains of bio-agents, could be advantageous in controlling noxious and problematic weeds. In addition, allelopathic plants have been reported to be a feasible weed control alternative in drylands. For effective weed management in drylands, innovative resource conservation strategies are being advocated. Efforts must be made to use robotic weed control techniques in drylands. Priority should be given towards developing integrated weed management methods, which would go a long way to attain efficient weed management in dryland agriculture. It could be a useful approach to promote the use of herbicides sparingly, in conjunction with the other effective, cost-effective cultural practices, mechanical methods, and eco-friendly bio-control measures, as well as other good agricultural practices. Weed management methods that are both efficient and cost-effective are required to ensure higher crop productivity as well as farmers' net returns.

Furthermore, climate change research would provide more information on crop-weed associations in dryland areas, which would aid in developing effective weed management techniques.

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# Insect and Pest Management for Sustaining Crop Production Under Changing Climatic Patterns of Drylands

# 21

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## Abstract

Climate change is alarming, particularly for agriculturists as it severely impacts the development, distribution, and survival of insects and pests, affecting crop production globally. Over time, climate change is drastically tumbling the crop productivity in all the cropping systems, whereas the dryland agriculture with

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existing low productivity is immensely hit. While all the existing species in drylands, including humans, are coping with extreme climate variations for millennia, future climate change predictions put dryland agriculture in a threat zone. Drylands support 38% of the world's population; therefore, climate change coupled with population growth and global food security draws the attention of scientists towards sustainable crop production under changing trends. The intermingling and intermixing of various biological, hydrological, and geographical systems plus the anthropogenic factors continuously amplify the changes in the dryland systems. All of this brings us to one challenge: developing pest management strategies suitable for changing climatic patterns. In this complex agrology framework, integrated pest management (IPM) strategies, especially those involving early monitoring of pests using prediction models, are a way to save the show. In this chapter, we will summarize the direct and indirect effects of climate change on crop production, the biology of insect pests, the changing pest scenarios, the efficacy of current pest management tactics, and the development of next-generation crop protection products. Finally, we will provide a perspective on the integration of best agronomic practices and crop protection measures to achieve the goal of sustainable crop production under changing climatic trends of drylands.

**Keywords**

Climate change · Dryland · Agriculture · Pest management · Production

## 21.1 Introduction

Climate change has been the talk of the hour globally due to its impact on almost all the natural and man-made ecosystems including terrestrial, hydrological, and agricultural systems (Rosenzweig et al. 2007). This led to a new discipline called "climate change biology" which studies the impacts of climate change on different biological systems (Hannah 2021). Talking about the agricultural system, climate change is one of the focal areas for agriculturists as it deeply affects the agriculture sector due to fluctuations in numerous factors including temperature, rainfall, $CO_2$, etc. that directly or indirectly influence crop and livestock production (Adams et al.

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1998). Hulme (1996) categorized these climatic conditions that affect agriculture into four major groups, namely, temperature, water runoff, carbon dioxide, and extreme conditions (Jones and Hassan 1991). The agriculture production scenario worsens in extreme calamities such as droughts, floods, and windstorms and is alarming due to the uncertainties attached to climate change (Jones and Hassan 1991). A global yield reduction of 3.8% maize and 5.5% wheat is predicted due to the changing climatic conditions (Lobell et al. 2011).

There is no denying the fact that the earth is getting hotter and over the past 100 years, major warming, constituting more than half of the total, occurred in the drylands. The drylands are described in terms of aridity index (AI) which is a function of average annual precipitation (P) and potential evapotranspiration (PET) (Middleton and Thomas 1997). The P/PET ratio is less than 0.65 in these areas, suggesting the AI is high which indicates scarcity in water supply in relation to atmospheric demand (Hulme 1996). The drylands share 42% of the total lithosphere of our planet, which comprises the grasslands, forests, cultivated land, and residential area. The drylands are very crucial for the developing countries as 58% of the drylands are marked in Asian and African countries (Laban et al. 2018). Scientists predicted that climate change will lead to the expansion of drylands, estimated to increase 10% by 2100 (Middleton and Thomas 1997). Climate change is most importantly marked by an increase in greenhouse gasses, like $CO_2$, which led to global warming. The increase in atmospheric temperature leads to the depletion of water resources in drylands, which drastically reduces agricultural productivity. The spatial and temporal variability in temperature and rainfall and complex biological, physical, and socio-economical systems accompanied by anthropogenic factors in these areas make it the worst-hit area for agriculture (Jones and Hassan 1991; IUCN 2019). The existing risks of droughts and floods in drylands will be amplified by the predicted rise in temperature (IPCC 2015; McKenzie 2009). Evidence suggests that in order to meet the yield requirements, cropland expansions occur at an approximate rate of 9% owing to yield reductions in drylands (Zaveri et al. 2020). Various crop models developed by the International Crops Research Institute for Semi-Arid Tropics (ICRISAT) to study the effects of climate change on crop growth, development, and productivity suggest that crop productivity will reduce under high-temperature regimes of drylands due to increased evapotranspiration and decreased LGP and crop duration, radiation interception, harvest index, and biomass accumulation (Jat et al. 2012).

It is predicted that the probability of strident and plausible impacts on agriculture and related species, especially the ones vulnerable, is inevitable and is thought to increase with time (IPCC 2015). Among the vulnerable species are the insect pests which are feared to be affected adversely by the changing climatic conditions of drylands leading to changes in the insect pest scenario and the onset of new pest species. Pest population dynamics including insect development, reproduction, survival, and spread along with their interaction with other pest species and natural enemies completely change with the increasing temperatures (Prakash et al. 2014). It is also thought that this rapid dynamic change in the insect population not only increases the rate of insect food consumption but also increases the risk of pesticide resistance development (Dillon et al. 2010; Matzrafi 2019; Pu et al. 2020). Consequently, many insect species have now shifted to low pest risk areas as well due to these climatic changes (Bebber et al. 2013).

## 21.2 Effects of Climate Change in Drylands

### 21.2.1 Insect Pest Biology

The vulnerability of agriculture to pest threat is increasing with the rise of temperature around the planet. It is anticipated that by the end of the twenty-first century, the global temperature would rise by at least 4 °C (Brown and Caldeira 2017). An increase in temperature, $CO_2$ level, reduced humidity, and frequent precipitation severely affect insect biology and ultimately the extent of crop losses. Temperature plays an important role in regulating insect growth, survival, and reproduction. Insects have a greater tendency to flourish in hotter temperatures and this allows them to feed more and reproduce more. Increased temperature can have direct effects on insects like elevating the developmental rates of insects and making them more heat tolerant (Harvey et al. 2020). In dryland areas, drier conditions often lead to the reduced production of secondary metabolites which are involved in plant defenses and increase the concentration of amino acids in plants which makes the plant more nutritious for insects to feed. Therefore, some insects perform better on water-deficit plants (White 1969; Maxmen 2013). However, this performance is displayed for a shorter period. In the case of sap-sucking insects like aphids, they can feed during the dry spells, but as the plants become water-stressed, there is a decline in fluid pressure in phloem cells which negatively impacts the aphid feeding (Huberty and Denno 2004). Growing maize at higher temperatures and under wet conditions leads to detrimental effects on the performance of herbivore *Bicyclus anynana*. These conditions led to a decrease in the herbivore's body weight, fat content, storage reserves, and phenoloxidase activity. These are the indirect consequences on herbivores mediated by variation in host plant quality due to climate change (Kuczyk et al. 2021).

The potato tuber moth outbreaks are more prevalent in Peru during hotter and drier years as compared to the usual conditions. The higher temperature in combination with less rainfall does not help in washing off the moths from the leaves and stems of the potato plant. Moreover, dry conditions produce cracks in soil which allow the larvae to move into the soil to feed on tuber (Kroschel et al. 2013). It is also expected that an increase in global temperature could expand the range of pest distribution. The pests which are now restricted to tropical regions only could move to temperate regions due to temperature changes. In sub-Saharan Africa, rice is among the major crops cultivated in different countries. It is severely affected by the attack of flea beetles of *Chaetocnema pulla* species group which is also a vector of rice yellow mottle virus disease. This disease causes 80–100% yield loss. Beetles spreading the virus make the condition worse. Currently, this beetle is posing problems to rice crops in Madagascar and Western and Central-Eastern Africa.

Future predictions based on climate changes concerning increasing temperature over the years suggested the faster dispersal of this beetle to some territories of Sudan, South Sudan, Cameroon, Nigeria, Zimbabwe, Democratic Republic of the Congo, and the Republic of South Africa. These examples suggest that in dryland land areas, climate change is playing a big role in increasing the risk of pest attack to different crops, expanding the range of insect population (Iannella et al. 2021).

Insects can get well adapted to their surroundings. For dryland areas also, to avoid the harsh climatic conditions and to thrive well, insects undergo physiological, morphological, and behavioral modifications. Some insects have a protective layer of hair around their body to prevent the loss of water during high heat waves and to reduce heat absorption by the body. They also spend much of their time underground in the soil or somewhere where the conditions are more favorable to live, and in such a way insects can escape the outside hotter environment. For example, in dryland areas, the dormancy of larvae of *Sesamia* occurs in the stalks of the sorghum plant in the hot summer season. However, in the case of irrigated areas, the dormancy of *Sesamia* occurs much later from the summers.

### 21.2.2 Pest Status

When insects escape their natural regulation via natural control agents, they uplift their status to pests, causing harm to humankind. Insects carried to a new region by human activities reduce the availability of particular natural enemies in the new place, thereby amplifying the pest population. Lack of natural control over pest populations helps the pest to achieve the levels where it can start causing economic damage (e.g., swarms of locusts grazing the farms). Climate change has a significant impact on the status of various agricultural insect pests. Researchers use different methods to forecast how the variation in temperature and precipitation may affect the existing status of insect pests, their abundance, and distributions. Changing climatic conditions has resulted in several pest outbreaks around the world. The warmer climate has facilitated the spread of fall armyworm *Spodoptera frugiperda* across countries attacking maize and millets including sorghum.

Another most devastating spreading pest is the desert locust, which has caused menace in the fields of African and Southeast Asian countries. Dessert locus usually lives in its solitary phase, but under certain circumstances, they change their behavior to the gregarious phase where their population becomes dense. The only single climatic factor does not result in huge outbreaks; instead a combination of rising temperature, heavy rainfalls preceded by multiple cyclones, and strong winds has provided a favorable environment for locust breeding, its development, and migration (Salih et al. 2020; Meynard et al. 2020). Desert locust consumes a variety of green vegetation including crops, shrubs, grasses, and trees. This shows the stronger impact of changing climatic conditions on pests and encourages them to thrive as major pests, thus resulting in risking food security. This not only affects the small-scale farmers and their livelihoods but also the people residing in countries where food availability is already at risk.

### 21.2.3 Invasive Insect Species

Invasive species pose a greater problem to agriculture success and can severely affect food security. These are the non-native species that are introduced to new geographical areas as a result of man-made activities. Due to increased global warming, globalization, high trade, international travel, and tourism, the introduction of invasive species to countries where they were not previously present is expected to be more. In the United States, crop loss of almost $40 billion is estimated to occur from invasive species present in the cropland and forest areas (Paini et al. 2016). As the invasive pests move from their native place to a completely new place, they avoid their regulation by their natural enemies like predators or parasitoids and attack on native plants. Recent examples of the most serious invasive pests around the world include desert locust *Schistocerca gregaria* movement from South Africa to East Asia, fall armyworm invasion in India, red turpentine beetle *Dendroctonus valens* that originated from North America and invaded China, spotted lanternfly introduction in North America native to China, and Asian tiger mosquito *Aedes albopictus* invasion in South America (Venette and Hutchison 2021).

Climate change inflicts direct effects on invasive pest biology and their behavior. The introduction of these pests, their establishment in the non-native area, distribution, and the success of their mitigation tactics are projected to be impacted by climate change. Global warming has a direct effect on plant physiology, like changes in the flowering time of temperate plant species; this facilitates the introduction of new pests to new regions and causes crop losses. Recently in 2020, the outbreak of desert locust *S. gregaria* in drylands of African countries and its movement to Southeast Asia have displayed a great example of how climate change has imposed severe threats to food security across the nations. High temperature coupled with precipitations and heavy winds provided favorable environmental conditions for its reproduction, growth, and movement. This explains that climate change played a significant part in providing conditions suitable for locust outbreaks (Karthik et al. 2021). Some insects have the ability to thermoregulate to overcome the harsh temperature and environmental conditions, increasing their possibility to invade the new geographic region. In the case of *S. gregaria*, it uses different thermoregulatory strategies like perching, stilting, and blending with vegetation to maintain their body temperature up to 40 °C to sustain the extreme temperature of 28–56 °C (Maeno et al. 2021).

Other invasive species include fall armyworm (FAW), *S. frugiperda*, which is a chewing herbivore that causes severe devouring of the host plant. This pest has previously invaded Africa, but in 2018 and 2019, it has been distributed to many countries like China, Indonesia, Australia, India, Japan, Thailand, and Myanmar. Undoubtedly, the increase in temperature has an impact on the developmental rates of pests which affects their biology, dispersal, and richness. Insects grow and develop in the defined temperature range which is suitable for their body but changes in the temperature can influence their development rates, reproduction, and life cycle and ultimately affect their subsistence. Their body metabolism increases when there is an increase in ambient temperature closer to a thermal optimum of pests (Karthik et al. 2021). Due to the multivoltine nature of FAW, it is anticipated to have more generations per year due to the effect of climate change (Sparks et al. 2007).

## 21.3 Impact on Pest Management Strategies

### 21.3.1 Chemical Control

The use of pesticides is the first choice of farmers for the control of pests and it is preferred over the other control methods due to its easy availability and quick and sure action against the target organisms. On the other hand, ill effects such as pest resistance, resurgence, secondary pest outbreak, and destruction of natural enemies may occur (Khan et al. 2011). However, the injudicious use of synthetic pesticides results in human health hazards, environmental pollution, and pest resurgence (Sharma 2014). Therefore, the choice of pesticide plays a key role in sustainable crop production in dryland areas. Based on the residue persistence of pesticides, less persistent chemicals can be used. Indiscriminate use of pesticides may interfere with plant development and help in managing crop production by killing competitive vegetation. But increased pesticide usage may affect soil quality (Arias-Estévez et al. 2008), food safety (Liu et al. 1995), human health (Nawaz et al. 2014), aquatic species (Skevas et al. 2013), and beneficial insects (Mullen et al. 1997). However, deployment of plant origin insecticides, growth regulators, attractants, and even synthetic pyrethroids can fit well in the IPM.

Due to the change in the climatic pattern of the dryland areas, there may be the occurrence of an increase in insect pest outbreaks, and it will eventually increase chemical usage which is likely to have a negative effect on the environment. Insect pests under changing climatic patterns of drylands for sustainable crop production can be managed by using suitable crop protection chemicals. However, in dryland areas, the effectiveness of crop protection chemicals could be affected due to changes in temperature, precipitation patterns, and physiological and morphological changes of crop plants (Coakley et al. 1999). Before insects establish themselves in protected feeding sites and to avoid the problem of resistance, the synchronization of the use of pesticides at the time of egg hatching and early instars of pests results in the best control. The time gap between pesticide application and weather conditions is the major cause for the loss of pesticides (Blenkinsop et al. 2008; Nolan et al. 2008). Higher temperatures in dryland areas can cause faster uptake of pesticides by the plants and ultimately increase the toxicity to pests. Pertaining to the efficacy of insecticides, there is the belief that some of the pesticides may result in greater toxicity to insect pests with the increasing temperature (Noyes and Lema 2015; Noyes et al. 2009). However, de Beeck et al. (2017) reported chlorpyrifos degradation and hydrolysis at higher temperatures that result in reduced mortality and less oxidative damage to insect pests (Hooper et al. 2013). Also, an increased temperature results in volatilization loss of pesticides (Otieno et al. 2013). Likewise, rainfall can result in increased pesticide wash-off and ultimately reduce the efficiency of pesticides to control the pest. To avoid pesticide wash-off instead of liquid, the use of granular formulations is less liable to be washed off by rainfall and also has lower drift instead of foliar spray applications.

In dryland areas, an increase in pest infestation results in the greater use of chemical pesticides. On the other hand, excess usage of pesticide could have detrimental effects on other beneficial organisms and ultimately results in the greater loss of crops due to the abundance of pests in the absence of biocontrol agents. Under changing climatic conditions, medium-range forecasting of weather can help in the prediction of rainfall patterns that will be helpful to avoid the application of pesticides under impending rainy conditions. Regular monitoring helps to undertake control interventions at the right time, thus helping in the easy and effective management of the small population of pests in dryland areas. Generally, pesticide losses are mainly affected by the time gap between extreme weather conditions and pesticide application (Blenkinsop et al. 2008; Nolan et al. 2008). Therefore, it is crucial to develop novel molecules which can balance the ill-effects of conventional chemicals and reduce the impact on natural enemies.

### 21.3.2 Cultural and Physical Control

To avoid insect pest damage in dryland areas, there is a need for suitable control tactics. Cultural methods are eco-safe as well as sustainable and do not require any additional budget for the control of insect pests. Alteration of cropping system, including crop production practices like crop variety selection, sowing, intercultural operations such as tillage, sanitation, crop irrigation activities, pruning and thinning, etc., can be adopted in the agro-ecosystem for sustainable crop production in dryland areas. So, there is a necessity for planning these activities in advance. These activities make the environment less attractive for pest establishment, dispersal, growth, reproduction, and survival, ultimately helping in reducing the pest population (Reddy 2016). Regular cultural practices can help in eliminating the carryover of pest populations (Koul et al. 2004). Other activities like crop mulching and composting are responsible for enhancing the spiders, earthworms, predators, and parasitoid populations that are responsible for controlling insect pests (Thomson and Hoffmann 2007). Contrastingly, the addition of large amounts of decomposable organic matter in the surface soil may stimulate the population of white grubs *Holotrichia oblita* or cutworms *Agrotis ipsilon and Agrotis segetum* that would result in the complete loss of the crop by cutting the roots of cereals under severe incidence (Giller et al. 2009). Reduced tillage in the field favors natural enemy populations (Sharley et al. 2008). Inadequate use of fertilizers may increase the insect population; therefore, need-based use of a pesticide may reduce the infestation of insect pests and help in sustaining crop production in dryland areas (Litsinger 1994). Intercropping in dryland areas has huge importance for the management of pests such as dryland rice intercropped with cotton or pigeon pea, resulting in lowering the number of green leafhoppers and white-backed planthoppers (Satpathy et al. 1997). Intercropping rice with *Pontederia cordata* reduced 33–34% of infestation of the rice leaf folder (Xiang et al. 2021). In dryland areas, cover crops have been shown to enhance the ground beetles and natural enemies' population for controlling insect pests (DuPre et al. 2021). Cover crops can provide habitat and food for several beneficial organisms (Jian et al. 2020).

Crop planting in dryland areas can inhibit many aquatic insects. Pruning, thinning, and clipping off of seedlings inhibit egg-laying of many insects, hence reducing the risk of insect pest infestation in the field. The movement of pests can be inhibited by installing barriers that help to reduce the risk of insect pests such as non-flying armyworm larvae, ants, locust nymphs, chinch bugs, etc. from one field to another field. Plowing of fields exposes insect pests to extreme weather conditions and straw burning can kill them by heat. Dense planting of crops may interfere with crop growth, its development, and microclimate and cause obstructions for flying insects (Litsinger 1994). On the other hand, flooding conditions in the field may kill soil-inhabiting insect pests such as armyworm, cutworm, etc. Trapping insects using sticky colored traps may reduce the infestation of pests. Adhikari and Menalled (2018), reported higher diversity of ground beetles and weeds in organic fields compared to conventionally managed wheat fields, enhanced conservation biological control, and sustainable agriculture in dryland cropping systems. *Drosophila melanogaster* fecundity was better under the influence of both temperature and relative humidity rather than individually (Maurya et al. 2021). Similarly, the lower incidence of *Riptortus pedestris* and *Clavigralla gibbosa* in early sown cowpea was due to their negative correlation with relative humidity, rainfall, and rainy days in the dryland ecosystem (Prasad et al. 2021). Mulching shows an abundance of parasitoid Hymenoptera, ground beetles, and spiders collected with pitfall traps; also in the canopy cover, the number of parasitic and predatory Diptera and predatory Hemiptera was increased in vineyard fields (Thomson and Hoffmann 2007).

### 21.3.3 Host Plant Resistance

The use of insect-resistant crops has revolutionized the area of pest management strategies. The insect-proof plants reduce the insect pest population in an eco-friendly manner (Chakravarthy et al. 2019). The ability of insects to develop resistance against insecticidal traits calls for the development of novel and durable pest management strategies. While the host plant resistance acts as a sustainable practice to manage insect pests, the duration of development of insect-resistant plants, the risk of development of resistance in insects, and specifically the abiotic factors influence the efficacy of insect-resistant plants are some of the bottlenecks in the area of host plant resistance (Stout 2014). In previous decades, host plant resistance has made significant progress and acquired sufficient space to become a part of integrated pest management programs. Despite the significant progress, there has been a potential lag in translating the research to practical solutions.

Abiotic factors play an important role in utilizing insect-resistant crops since they possess the ability to modulate the plant defense responses to insects. For instance, wild cotton plants under dry conditions have been shown to enhance the plant defenses and consequently decrease the insect attack (Abdala-Roberts et al. 2019). Contrastingly, drought stress did not elevate the plant defenses such as jasmonates and protease inhibitors in tomatoes (Ximénez-Embún et al. 2017). Several reports show that sap-sucking insects are predicted to cause more damage to drought-stressed plants and subsequently lead to cause more vector-borne diseases (Nachappa et al. 2016; Sconiers and Eubanks 2017; Florencio-Ortiz et al. 2018). Monarch caterpillars have also been shown to grow better on water-deficit milkweed plants (Hahn and Maron 2018). However, the variability in insect performance depends on the intensity of water-deficit and herbivore type.

Specifically, thrips and whiteflies are the main vectors of plant pathogens. Thus, abiotic factors may not only affect the insect feeding but also involve the risk of higher viral disease incidence. Thrips have been reported to cause significant damage in cotton and onions under water-deficit conditions (Fournier et al. 1995; Sconiers and Eubanks 2017). Simultaneously, it could be more complex for insects such as whiteflies. Whiteflies prefer to grow on plants under dry conditions at the expense of lower oviposition rates (Paris et al. 1993; Inbar et al. 2001). Thus, understanding insect biology is very crucial while engineering plants for insect resistance. Plants not only respond locally to defend against insects, but they also transmit systemic signals to other parts of the plants. The resistance signals can also travel from aboveground to belowground and vice versa. In maize, it has been shown that belowground herbivory induces aboveground resistance to insects and the resistance levels have been associated with the reduced quality of the leaves due to in-planta hydraulic changes (Erb et al. 2011). This study provides another perspective on induced plant resistance under dry conditions. Recently, the fall armyworm, *Spodoptera frugiperda*, has expanded its range in the United States and caused significant yield losses and the underlying reasons have been mainly attributed to climate change (Miedaner and Juroszek 2021).

Antixenosis, antibiosis, and tolerance constitute the main categories of host plant resistance (Smith 2004). Antibiosis has been the most extensively studied category among the plant breeding approaches for pest management (Sharma and Ortiz 2002; Stout 2014). Therefore, it becomes crucial to explore the antixenosis and tolerance categories of host plant resistance in order to compensate for plant yield losses caused by insect damage (Peterson et al. 2017; Grover et al. 2020). Though dry conditions can alter the plant defense status, it is still a reliable and stable strategy compared to others. But there is a need for improvements in insect resistance breeding approaches that are suitable for dryland farming. Breeding for drought-tolerant and insect-resistant traits together can help to manage the insect pest management in changing trends.

Simultaneously, there will be a strong need to assess the risk of the spread of other insects and pathogens favored by dry conditions in the breeding process (Fig. 21.1).

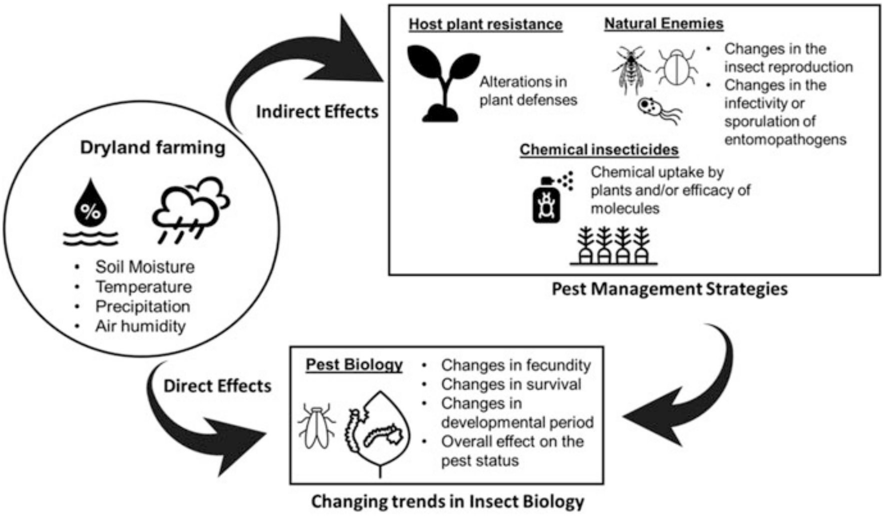

**Fig. 21.1** Changing climatic conditions in drylands can impact insect pests indirectly and directly. Changing climatic trends affect the plant resistance, biology of natural enemies, and chemical insecticide efficacy, which further impact the pest biology positively or negatively. Direct effects of changing climate involve changes in pest biology

### 21.3.4 Biological Control

Biological control involves the utilization of living organisms, predators, parasites, and pathogens for the control of pests. The strategy is considered safe and eco-friendly, compatible with other IPM technologies. Since the biological agents are slow-acting and take more time to be effective, they are less used by farmers. Though there are reports suggesting the decreased abundance of the predators and parasitoids in dryland landscapes, this approach could act as a safeguard to reduce the crop yield losses caused by insect damage, if managed sustainably (Adhikari et al. 2019). Abiotic factors can impact the biology of insect pests and their natural enemies as well. Therefore, it is very important to understand insect biology with changing trends and quantify the impact of dryland conditions on the efficacy of natural enemies. In order to minimize the reduction in natural enemies' performance, several agronomic measures can be adopted. For instance, cover crops have been suggested to enhance communities of ground beetles, a natural predator of insect pests, in dryland cropping systems (DuPre et al. 2021). Also, multi-cropping has been suggested over monoculture for effective pest management (Palmu et al. 2014).

Furthermore, organic farming in dryland landscapes has been shown to increase the biodiversity of plants supporting natural enemies' populations by strengthening ecological networks (Adhikari et al. 2019). Entomopathogenic nematodes (EPNs) can also serve as a biocontrol agent to control the insect pests. In dryland landscapes, EPNs have been suggested to be sprayed with polymer gel to prevent nematode desiccation (Shapiro-Ilan et al. 2016). Also, further investigations are required to identify the drought-tolerant EPN strains which could be better utilized in dryland farming. Moreover, the other category of natural enemies to insects, entomopathogens, can vary in their effectiveness from one location to another depending on the weather conditions (Mandakini and Manamgoda 2021).

## 21.4 Conclusions

Climate change is inevitable, and its effects are visible on the insect pest population, directly and indirectly affecting agriculture (Chander et al. 2016). The challenging issue of food security has made dryland agriculture more and more important; especially in these changing climate times, we need to develop adaptation strategies for sustainable agriculture production (Jat et al. 2012). Some of these strategies include efficient utilization and management of natural resources and use of genetically improved crops, coupled with adequate socio-economic policies. Diversifying agriculture systems through conservation agriculture is another strategy that can help combat these changes (Pedrick 2012). Climate change mitigation in drylands can be addressed by the conservation and restoration of ecosystems in drylands. The dryland ecosystem can be enriched by perennial plants which will improve the soil health and increase CO2 sequestration and population of predators in a well-maintained ecosystem. The adoption of climate resilience strategies in drylands involves the use of drought-tolerant crops, drought-resistant crop varieties, water-efficient agronomic practices, modified existing pest management strategies, and development of next-generation crop protection compounds that work efficiently in high temperatures (IUCN 2019).

Besides improving pest management strategies, it also becomes important to evaluate and monitor climate change critically and early predict the changes in the insect populations and use the global information system (GIS) for invasive species and assessment of pest risk (Cook 1932). The use of new-generation pesticides, genetically modified organisms, biotechnological approaches, etc. is one of the latest reliable techniques which need more future explorations. The use of artificial neural networks (ANN) in combination with appropriate databases and software such as semi-automated digital image encoding systems might have practical implications in studying insect systems (Fedor et al. 2009). The trends in the pest population of drylands due to dynamic climatic factors can be predicted using various climate models (Tang et al. 2021). The use of deep learning and image-based technologies is important for correct insect pest diagnosis (Xin and Wang 2021). The disease forecasting models earlier based on algorithms can be strengthened now by the use of deep learning and AI-based tools. These strategies coupled with adequate research and extension can help mitigate some of the challenges and problems faced by the agriculture sector in drylands due to the changing climate and onset of rapid variations in insect pest scenarios.

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# Potential Effects of Future Climate Changes in Pest Scenario

# 22

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## Abstract

Climate change with multifaceted stressors and impacts is among the defining challenges for ecological sciences, human beings, and planet Earth in the twenty-first century. Nevertheless, evidence of scientific literature on climate change and the quality of climate models for predicting future climatic changes has become sophisticated in recent decades; the account of altered pest dynamics on crop production and other ecological cycles due to climate change demands significant attention as well. In this chapter, we discussed how climate change such as elevated temperatures, high $CO_2$ levels, and erratic precipitation patterns leading to droughts, floods, and other extreme weather conditions may influence pests' populations. For instance, climate change can trigger changes such as the expansion of pest distribution in spatial and temporal bases, increased pest infestation intensity, crop yield loss, increased risk of invasive pest species occurrence, increased transmission of vector-borne diseases, reduced success of biological control, reduced efficacy of current integrated pest management strategies, and changes in pest population dynamics, pest biology and their physiology such as the number of generations, life cycle, changes in overwintering patterns, and extinction. Recent data and studies projecting the impacts of climate change on pest scenarios based on climatic models are discussed. We also highlighted the role of climate models and their significance in predicting the pest outbreak under the changing climate scenarios to mitigate the damage to some extent. The climate change effects are studied using observations and experiments over gradients of elevation, latitude, and urbanization. This chapter provides a theoretical basis and reference for crop improvement and pest management under future climate changes.

## Keywords

Agriculture · Climate change · Modeling · Pests · Warming trends

## 22.1 Introduction

Insects are the ectotherms due to which their body temperature is affected under the climatic variability and external environmental conditions. Owing to this, climate change could highly affect the status of agricultural insect pest throughout the world. Climate influences the metabolic rates, speed of development, and life-history traits of an organism causing several changes under climate change events (Luedeling et al. 2011). Climate change could accelerate pest growth rate, a high number of generations per year, increased risk of the attack from exotic pests, change in the geographical distribution of the pests, and extension of life cycle under certain circumstances. Global temperature has increased over the last few decades, and it is predicted that there will be an increment of 1.5–5.1 °C by 2100 (Pachauri and Meyer 2014). Ectotherm organisms, especially insect pests, quickly respond to these alterations. Hence, it is imperative to study the distribution and virulence patterns of insect pests to maintain global food security under climate change to sustain the rapidly increasing human population.

The industrial revolution is believed to be the triggering point for the rise of $CO_2$ levels from 280 umol/mol, which now has surpassed 500 umol/mol (Hoegh-Guldberg et al. 2019). $CO_2$ is an important gas regulating various biological processes in plants, especially photosynthesis, weather, and global temperature. Furthermore, increased concentration of the gases after the post-industrial revolution led to mean global temperature 1 °C higher than pre-industrial revolution. The combination of higher temperature and elevated carbon dioxide concentration had expanded the insect pest distribution northward since the 1970s, reduced the winter die of insect pests resulting in high density to feed on spring outgrowth, and leads to phenology changes with earlier emergence and dispersal of overwintering insect pests (Tougeron et al. 2020).

In temperate regions, higher climatic variability, extended growing seasons, warmer average temperature, and lower climate predictability constitute the important aspects of global climate change (Sutherst et al. 2011). Insect pests respond to climate change in three ways, either due to local adaptations or plasticity. They can adjust the phenology to cope with the current climate, shift to a new geographic distribution to match their climate requirements, or adjust their tolerance capacities to the climate pattern's local changes (Sutherst et al. 2011). Especially for the insect's pests in polar and temperate regions, changes in phenology are the most important responses to climate change. Furthermore, insect pests in these regions are shown to reproduce earlier to delay the diapause and increase the number of generations per year (Biber-Freudenberger et al. 2016).

To understand the effect of future climate change on insect pest distribution and virulence, it is essential to study how current and past climatic changes affected the seasonal phenology, distribution, and relative abundance of the organisms. It is clear from the literature that catastrophic climatic events caused several pests to outbreak globally, and the amount of variation accounted for by these climatic conditions. Several studies have shown the effect of climate on the insect pest's population dynamics, but still building such predictive process-based change of models is challenging. Commonly, correlation analysis is used to determine the relationship between the population dynamics and climatic variables, assuming additive covariable in the statistical models (Stenseth et al. 2002). However, recent studies have shown that the effect of the different climatic variables can't be considered additive into the traditional statistical models; however, complex higher-order interactions need to be considered (Estay et al. 2009). Although climate change impacts several flora and fauna, the effects of climate change on insect pests' scenarios and hence their management are the focus of this book chapter.

## 22.2 Effect of Elevated Temperature on Pest Dynamics

Climate change and global warming have significant impacts on agricultural production and on agricultural insect pests worldwide (Skendžić et al. 2021). Temperature is one the most important climatic parameters when it comes to agricultural pests like insects. Temperature is probably the single most important environmental factor influencing their behavior, distribution, development, survival, and reproduction. Lower values of temperature range where insects remain active from egg to adult stage are called "threshold of development." Within the favorable range, there is an optimum temperature at which most of the individuals of a species complete their development. Exposure to temperatures on either side of the range produces an adverse impact on the insect.

Insects are poikilotherms, which means their body temperature is the same as their environment, and temperature has a direct effect on their developmental rate (Bale et al. 2002). All insects will be affected by the increasing temperature but the degree at which the warming will affect will vary as the climate change is not evenly distributed on the globe (Bale and Hayward 2010). Even a small degree change in the temperature will have a major impact on the insect's life cycle, mainly survival and reproduction. The life cycle of insects may become shorter and that will increase the population (Bale and Hayward 2010). Insects from temperate and tropical regions will have different impacts. As temperature increases, it is having a potential impact on insect pests, mainly (a) geographical distribution, (b) increase in the number of generations, (c) overwintering survival, (d) impacts on biological control, and (e) invasive species as described below:

### 22.2.1 Increase in Geographical Range

One of the major impacts of temperature increase will be on distribution of insects in geographical range. There will be acceleration in the rate of geographical range, as many insects rely on temperature and not on vegetation to define geographical range. The species will move towards higher altitudes and low temperature areas, which were not preferred until now that they become the new hotspot for insect species. By 2055, the ranges of insect pests are expected to shift to higher altitudes. For example, the European corn borer (*Ostrinia nubilalis* Hübner) has moved to 1000 km northward (Porter et al. 1991). In general, when it comes to insect diversity, the minimum temperature is more important than maximum temperature. Researchers have shown that a greater number of species have ranges from tropical to subtropical and finally to temperate region (Kuchlein and Ellis 1997; Parmesan and Yohe 2003; Sharma et al. 2005, 2010; Logan et al. 2003). And this will increase the population of insects from tropical regions (Cannon 1998; Bale et al. 2002; Diffenbaugh et al. 2008).

This might create a major crop pest outbreak and may cause huge loss to farmers (Kannan and James 2009). At the same time in temperate region the overwinter survival time will increase, for example, one of the major migratory pests, corn earworm (*Helicoverpa armigera* Boddie), has bigger range altitude-wise which can also cause damage to maize in the United States (Diffenbaugh et al. 2008) as well as some crops like cotton and pulses in Asia (Sharma et al. 2005, 2010). Most importantly, this new range expansion could change the local diversity and finally the balance of the ecosystem (Skendžić et al. 2021).

### 22.2.2 Increase in the Number of Generations of Insect Pest

Temperature plays a very important role in the growth and development of cold-blooded insects. The studies on model prediction suggest that with a 2 °C temperature increase insects could have one to five additional life cycles per year (Martín-Vertedor et al. 2010). With increasing temperature, there will be a direct impact on insects of temperate regions which will have lower winter mortality rate and higher insect population in the following growing season. Due to global warming and increasing temperature, insects can have early adult emergence and increase in flight duration, for example, the European grapevine moth (*Lobesia botrana* Denis and Schiffermüller). The early emergence increased voltinism (number of generations come out per year) in Spain. Voltinism is the key change which provides information about the insects' adaptivity to global warming and can help us to understand the diversity of different species in particular environments per year (Martín-Vertedor et al. 2010).

### 22.2.3 Overwintering Survival

Insect from the temperate regions have to go through a harsh winter environment. To tolerate the cold winter insects must apply different strategies to survive. They do these via two different phases, one avoiding winter season through a phase called diapause, or they change their behavioral response to harsh environments and migrate (Bale and Hayward 2010). This physiological state diapause helps insects to suspend further development, mainly dropping the metabolic rate at egg/larvae/pupal stage during winter, and again gain active growth during summer when adult comes out. Diapause can be terminated via changes in environmental factors like temperature, humidity, and photoperiod. Research has shown that global warming is happening mostly during the winter season at higher altitudes (Skendžić et al. 2021). This implies that even increasing the temperature range of 1–5 °C would affect the diapause duration and development would occur at a faster rate. This in turn can decrease the winter mortality and increase early emergence of insects with high populations, which can damage a greater number of crops (Harrington et al. 2001; Sharma et al. 2005, 2010). The 1-month early onset of flight of anholocyclic aphid species in the United Kingdom is one of the examples for climate warming and overwintering survival. The aphids can migrate earlier in spring, and this can cause high damage to the crops, simultaneously causing long period virus infection (Cannon 1998).

### 22.2.4 Impact on Biocontrol Agents

Phytophagous insects are in synchronization with their host plant as well as their natural enemies. The tritrophic interaction between the host plant, the herbivore insect, and their natural enemies plays an important role in population dynamics of insect pests. Temperature can have a severe impact on the desynchronization between the insect pest and their natural enemies, which can have a negative impact on the role of natural enemies as biological control (Welch and Harwood 2014). In case of specialist insects, increase in the temperature can have early emergence of natural enemies than the prey which can lead to extinction of some biological control (Hance et al. 2007). For example, a rise in the temperature disturbed the natural enemies of cereal leaf beetle (*Oulema melanopus* L.) as found by Evans et al. (2013). In some cases, the crop distribution changes due to climate change which can have a direct impact on pest population. The pest can grow faster in a new range without biological control. This suggests that natural enemies which are more generalists can be less affected by climate change and could be part of a pest management program (Crowder and Harwood 2014).

### 22.2.5 Impact on Invasive Species

The globalization and trading system used to be the core reason for new invasions but in recent times climate change plays a role in the introduction and establishment of a pest species in a new habitat. Insect pests are highly dependent on temperature (Vermeij 1996). Any change in the temperature allows these insects to grow faster in the new environment. Adapting to new food choices, plasticity helps the invasive species to develop better. For example, with more than 30 plant species as a food choice, it provided the successful invasion of *Drosophila suzukii* Matsumura (Poyet et al. 2015). Large shifts in the environment such as temperature change could help insect pests in thermal adaptation in new environments and provide new habitat.

## 22.3 Effect of Precipitation on Insect Pests

Changes in precipitation patterns affect the distribution and abundance of insect pests. Rainfall affects the incidence and activities of pests in terms of soil moisture and humidity levels or directly when exposed. Subject to climate change, there is a decline in the frequency of rainfall, whereas an increase in its intensity. Because of this, there are both heavy showers leading to floods and rainfall shortages causing drought spells. Uneven rainfall patterns have detrimental effects on the population of insect pests. For example, heavy rainfalls have an impact on the occurrence of small-bodied pests such as aphids, jassids, whiteflies, etc. on crops. Such heavy rainfalls tend to wash away the pests and thus reduce their incidence (Chander 2012). As a result of increased soil moisture, many insects are killed submerged in water. It also poses a great threat to the free-living insects in the soil as eggs, newly hatched larvae, or nymphs. A study conducted by Staley et al. in 2007 investigated the impact of increased summer rainfall and drought on the abundance of soil-dwelling fauna in grassland plots.

There was a rapid increase in the number of larvae of the dominant root-chewing insect species such as *Agriotes lineatus* L. in the upper soil because of increased summer rainfall events in contrast to the ambient and drought conditions. Another study showed that above-average precipitation would favor the spread of swede midge (*Contarinia nasturtii* Kieffer), a Eurasian pest of crucifers in North America (Olfert et al. 2006). High precipitation kills many young larvae of cabbage worm (*Pieris rapae* L.) and diamondback moth (*Plutella xylostella* L.) on cabbage. Extreme rainfall has a damaging effect on the boring insect eggs and newly hatched larvae such as the European corn borer (*O. nubilalis*), before boring into plants. Spread of red imported fire ant (*Solenopsis invicta* Buren), an invasive insect of citrus and livestock, is favored by rainfall.

Droughts affect the herbivore insect population by changing the nutritional quality of the plant tissues consumed by them, thereby affecting their performance (Holopainen et al. 2018). Different pests respond contrastingly to drought conditions. Generally, primary pests feeding on tree trunk such as moths boring on pine shoot or stem are negatively affected by drought, whereas bark beetles, leaf chewers, miners, gall makers, and sap feeders benefit from drier conditions. Soil deficient in moisture causes the plants to lose their biological functions and be more prone to insect pests (Zayan 2019). Drought-stressed plants can attract some insect species. For example, the harmful bark beetles can detect the ultrasonic acoustic emission produced because of the water columns in the xylem breaking apart due to moisture loss via transpiration. Secondary metabolites produced as a result of the stress make the plants more susceptible to insect attack (Yihdego et al. 2019).

Changes in precipitation patterns can impact insect pest predators, parasites, and diseases resulting in a complex dynamic. High humidity favors the fungal pathogens of insects, and their incidence would increase due to climate changes that extend periods of high humidity and would be reduced as a result of drier conditions.

## 22.4 Effect of Elevated $CO_2$ Concentrations on Insect Pests

Increased atmospheric concentration of $CO_2$ is expected to have a direct impact on insect feeding growth, distribution, and abundance. It is predicted that $CO_2$ concentrations will increase from current ambient levels of 540–970 ppm by the end of the twenty-first century (Houghton et al. 2015). There has been a 25% rise in $CO_2$ concentration already since the industrial revolution. The increase in greenhouse gases will have a severe impact on the atmospheric temperature which may increase from 1.4 to 5.8 °C by the end of the twenty-first century (Porter et al. 1991; Anton 2008). Although the effects of a warming earth will influence all flora and fauna, including humans, this chapter will cover the effects of increased $CO_2$ concentrations on insects only.

Elevated atmospheric $CO_2$ concentration could have a direct effect on plant physiology such as increased plant growth through increased plant assimilation of $CO_2$ which will influence both quality and quantity of food for insect herbivores. Carbon dioxide is a key chemical compound for plant photosynthesis, a process by which plants synthesize their food from $CO_2$ and water in the presence of sunlight and green pigment chlorophyll. Due to higher $CO_2$ concentrations, carbon assimilation will increase; thereby plant growth and productivity will be improved. Photosynthetic rate will also be higher due to transpiration reduction, stomatal conductance, and better water and light-use efficiency (Woodward 1990). But increased $CO_2$ will also imbalance the C/N ratio as nitrogen concentration in plant foliage will be decreased and plant quality will decline.

But all plants will not respond in a similar manner. For example, C3 and C4 plants will have different responses to higher atmospheric $CO_2$ concentrations as C3 plants are more sensitive to change in $CO_2$ concentrations than C4 plants (Tubiello et al. 2002; Skendžić et al. 2021). The C3 plants uses the Calvin cycle for $CO_2$ fixation and the product of photosynthesis is a 3-carbon molecule, whereas the photosynthesis product in C4 plants is a 4-carbon molecule and the photosynthetic efficiency is also 50% higher for C4 plants than C3 plants. Because in C3 plants, mesophyll cells inside the chloroplast are only placed for plant photosynthesis, in C4 plants, it takes place in both chloroplast and bundle sheath cells (Skendžić et al. 2021). Therefore, elevated $CO_2$ will have a varied impact on C3 and C4 plants. For instance, in a study conducted to compare C3 sedge and C4 grass in a wetland habitat, it was found that foliar nitrogen concentrations decreased in C3 edge with higher $CO_2$ concentrations. On the other hand, C4 grass had higher foliar water concentration which leads to higher fungal infection (Thompson and Drake 1994). In another study, paper birch and white pine also responded to elevated $CO_2$ concentrations differently, as foliar nitrogen and condensed tannin levels were increased in paper birch only (Roth and Lindroth 1994). All these compounds can affect insect feeding by making plants unsuitable or more vulnerable to insect damage.

According to the carbon-nutrient balance hypothesis, under elevated $CO_2$ concentrations, all plant secondary metabolites containing carbon should increase (Hamilton et al. 2001). However, this does not seem to be the case for all the plants. For example, volatile terpenoids of peppermint and loblolly pine are unaffected under elevated $CO_2$ concentrations (Lincoln and Couvet 1989). On the other hand, higher C/N ratio due to increased $CO_2$ concentrations can reduce nitrogen concentration in plant foliage and thereby affects nitrogen-based plant defenses against insects (Williams et al. 1997; Zvereva and Kozlov 2006).

In a review article (Bezemer and Jones 1998), it was found that 29 out of 33 plant species had decreased nitrogen concentration by 15%, and only four plant species had slightly increased nitrogen concentration under elevated $CO_2$ conditions. On the other hand, carbohydrate levels were 47% higher in 17 out of 20 species. So, under elevated $CO_2$ concentrations plant quality declines due to a decrease in foliage nitrogen concentrations. Some studies have investigated the effects of elevated $CO_2$ on insect's growth and development under controlled environmental conditions. For instance, under elevated $CO_2$ conditions, leaf chewers can compensate for decreased nitrogen concentration by increasing leaf consumption (Whittaker 1999). Leaf chewers with chewing mouthparts feed on plant leaves intensively and leave only leaf skeleton or bared veins. While growing, leaf-chewing insects are capable of consuming plant tissues many times their own weight. However, this is not a very smart feeding strategy as insects are feeding on less nutritious and more fibrous plant parts which lead to large fecal droppings and most of the plant tissues are released undigested.

Besides overcompensated feeding, larval mortality and developmental rates are also adversely affected under increased $CO_2$ concentrations. However, effects on pupal weight and developmental time are almost negligible and non-significant. For example, in an experiment, buckeye butterflies (*Junonia coenia* Hübner) had higher mortality and larval developmental time when fed on buckthorn species such as *Plantago lanceolata* Mert. & W.D.J. Koch (Lamiales: Plantaginaceae) with higher $CO_2$ foliage concentration as compared to plants with ambient $CO_2$ (Fajer et al. 1989). However, this is not the case for all leaf-eating insects fed on high $CO_2$ foliage, as some insects had higher larval survival or no significant effect at all. For instance, when larvae of beet armyworm (*Spodoptera exigua* Hübner) were fed on sugarbeet *Beta vulgaris* L. (Caryophyllales: Amaranthaceae) and pigweed *Amaranthus hybridus* L. (Caryophyllales: Amaranthaceae) foliage under elevated and ambient $CO_2$ concentrations, larval survival was higher only on sugarbeet under high $CO_2$ concentrations and no significant difference in growth rates for any of the plants (Caulfield and Bunce 1994). But it is important to mention that leaf chewers have shown higher survival and growth rates when both insects and plants were reared under elevated $CO_2$ concentrations. But most of the experiments have been conducted using detached leaves or only plants grown under high $CO_2$. Therefore, varied responses to increased $CO_2$ concentrations have been documented among leaf eating insects but they are able to compensate for low-quality plants by increased food consumption.

Similarly, leaf miners are also able to compensate for low-quality food due to low nitrogen concentrations by increasing their food consumption but effects on larval mortality and pupal weight are more severe and significant (Whittaker 1999). As leaf miners are very selective feeders and feed inside plant leaf tissues with low amounts of cellulose which also provides them protection against predators and parasitoids, they are not as aggressive feeders as leaf chewers and are unable to get the required nutrition from low-quality plant leaves, even after compensated feeding. For instance, there was no significant difference in the leaf mined area by chrysanthemum leaf mining fly (*Chromatomyia syngenesiae* Hardy) on smooth sow thistle *Sonchus oleraceus* L. (Asterales: Asteraceae) plants with elevated or ambient $CO_2$ concentrations. Leaf miners did not exhibit compensated feeding, even though plant quality was reduced due to low nitrogen concentrations (Smith and Jones 1998). No compensatory feeding could be due to thicker plant leaves owing to elevated $CO_2$ concentrations. However, pupal weight was reduced, and overall developmental time was also increased under elevated $CO_2$ than ambient conditions.

On the other hand, unlike leaf miners, phloem or sap feeder insects have shown positive response to elevated $CO_2$ conditions. Sap-sucking insects such as aphids have sucking mouthparts and feed on plants by sucking the sap from softer tissues (xylem, phloem, or mesophyll cells) and hence will not be affected by reduced plant quality in a similar manner as leaf chewers. In another study by Wang and Nobel in 1995, it was found that phloem exudates from *Dactylopius opuntiae* Cockerell feeding on *Opuntia ficus-indica* L. (Caryophyllales: Cactaceae) had 5% more sucrose and 50% more mannose, but amino acids were reduced by 17% under elevated $CO_2$ than ambient conditions. Moreover, some phloem feeders have higher population sizes in response to higher $CO_2$ concentrations (Bezemer and Jones 1998).

Increased $CO_2$ concentrations will not only have direct effects on insect feeding, growth, and development but can also affect third trophic level and thereby bottom-down regulation as well. For instance, compensatory feeding by leaf chewers or leaf miners will prolong their feeding time which will make them vulnerable to predation and parasitism. Moreover, researchers conducted an experiment in a Florida scrub-oak community (Stiling et al. 1999) to determine the effects of increased $CO_2$ on leaf miner densities, their feeding rates, and levels of attack of natural enemies. They found reduced leaf miner densities on oak leaves, increased food consumption, and increased leaf miner mortality under elevated $CO_2$ conditions. They concluded that longer feeding time increased leaf miners' chances to predation, low-quality food made them weak and thereby increased parasitism, and lastly, longer mines due to increased food consumption could have attracted more natural enemies.

Furthermore, all these studies looked at the effect of increased $CO_2$ only, but elevated $CO_2$ would lead to increased temperatures as well, so it is vital to understand the effects of both factors and their interactions on insect's growth, feeding, development, and third trophic level. Another study conducted (Johns and Hughes 2002) looked at the interactive effects of elevated $CO_2$ and temperature on echium leaf miner (*Dialectica scalariella* Zeller) in Paterson's Curse, *Echium plantagineum* L. (Boraginales: Boraginaceae). It was found that at low temperatures, elevated $CO_2$ had non-significant effect on *D. scalariella* mortality. However, mortality was higher at high temperature and elevated $CO_2$. Body weight was also significantly reduced when both $CO_2$ and temperatures were increased. Because higher temperature leads to decreased developmental time and *D. scalariella* did not have enough time to compensate for low-quality food by increasing food consumption, this highlights the need to study the interactions of different climatic factors to determine their effects on plant-insect interactions, rather than focusing on one single factor.

## 22.5 Pest Management Under Climate Change Scenario

Pest management strategies are influenced by environment conditions. With elevated $CO_2$ and temperatures, erratic precipitation patterns, and other changing climate conditions, non-native species will move to new areas, plant-insect interactions will change and will be less predictable, and thus it will be difficult to predict how climate change will affect pest management strategies. Several lines of reasoning suggest that invasive plant species could maintain or even increase their fitness relative to other species under climate change due to several attributes such as better ability to "tolerate" new climates than the average species, rapid evolutionary change, high phenotypic plasticity (Maron et al. 2004), and broad environmental tolerances (Qian and Ricklefs 2006). Thus, for invasive species, strict quarantine measures will be needed to prevent the spread of species to new areas because of altered geographical and temporal distribution of species under climate change.

Changes in integrated pest management strategies will be required. Farming and cultural management will be needed to reduce pest outbreak and buildup of the natural enemy population by manipulating the diversity of the habitat, planting many varieties, or other tactics such as mulching and providing shelters to combat extreme temperatures and heavy rains. Crop diversification and refuge crops will increase the functional ecosystem diversity of the landscape which will be beneficial under rapidly changing climate (Lin 2011). Structural diversity can also reduce pest pressure such as unharvested strips of Lucerne can provide habitat for the natural enemies of corn earworm (*H. zea* Boddie). Furthermore, life-history traits of herbivorous insect pests and distribution of population of natural enemies will likely evolve in synchrony or asynchrony with their prey (Colinet et al. 2015). Natural enemies usually have less adaptive capacity to changing climate conditions than phytophagous insect pests, thereby reducing the effectiveness of biological control agents for suppressing hosts using biological control tactics (Wajnberg et al. 2016).

Lastly, for pesticides, which are one of the most sought pest controls worldwide, with the prediction of more insect pest outbreaks under climate change and the need to meet global food production, it is predicted that pesticide use will increase under changing climate conditions (Chakraborty and Newton 2011). Since the growth and reproductive output of insect pests will increase under elevated temperatures in the temperate regions, it is suggested that pesticide and fungicide output will also increase in the temperate regions (Ziska 2014). It is important to note that exposure to sublethal concentrations of pesticides could be an additional problem as it increases the cross tolerance to temperatures and insecticides. For example, the mortality of brown plant hopper (*Nilaparvata lugens* Stål), when exposed to sublethal concentrations (40 ppm) of triazophos insecticide at 40 °C, reduced from 94 to 50% and lethal time also increased by over 17 h. Furthermore, both Hsp70 and arginine kinase were upregulated, providing thermotolerance and enhanced survival, suggesting sublethal pesticide exposure could lead to cross tolerance to temperature (Ge et al. 2013). In addition, semiochemicals are an important part of integrated pest management and their effectiveness will be influenced under altered temperature regimes.

Weather-based forewarning systems can be efficiently used in the pest management decision process to evaluate the risk of outbreaks of economically damaging crop pests at present and future climate change scenarios. These warning systems with input information on weather, crop, and/or insects can advise farmers or crop growers when they need crop protection measures such as applying an insecticidal spray to prevent pest outbreaks from causing economic losses. These warning systems would be the integral element of integrated pest management (IPM) to reduce excessive use of chemical pesticides. Since these pest warning systems would be new technology and its adoption by growers will be slow, the government should provide several potential incentives for growers to adopt these warning systems. By utilizing risk assessment-based spray timing instead of traditional calendar-based pesticide sprays, growers can reduce the frequency of sprays, hence reducing the health and environmental hazards of chemical pesticide use. These pest warning systems will be an environmentally friendly alternative to growers. Furthermore, climate models combined with the environmental needs of a particular pest species can be utilized for forecasting the possible range of changes in pest distribution on a global scale. In addition, modeling the pest risk along with the responses of its host plants to climate change can improve the ability to predict the outcome of an insect infestation.

Multidisciplinary approaches focused on integrated rather than disciplinary science can also help to improve decision making and respond in times against pest risks such as for invasive species management. Additionally, IPM systems should be modified to improve the existing pest detection and control systems. Better understanding of the pest, host plants, environment, and their interactions should be given attention to allow crop advisors to make better pest decisions under climate change scenarios. Combining modified IPM with a weather-based pest forewarning system would help to choose relevant management strategies and respond efficiently to climate change.

## 22.6 Conclusions

Climate influences the speed of development, metabolic rate, and life-history traits of an organism, causing several changes under climate change events. The last few decades witnessed an unprecedented increase in temperature and carbon dioxide level, with unexpected precipitation changes worldwide. This chapter outlined different changes occurring in the incidence, distribution, and virulence of insect pests occurring globally with these catastrophic changes. Climate has affected the insect pest intensity, spatial and temporal distribution, reduced control of biological and chemical agents, invasion of new species to crop plants, phenology and life-history changes, and population dynamics. Furthermore, we provided methods of how pest management could be performed under the changing climate and with the development of climate and prediction models for insect pest distribution and attack, while helping to take preventive measures.

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# Impact of Climate Change on Plant Viral Diseases

# 23

G. Vamsi Krishna

## Abstract

Climate change refers to a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Atmospheric $CO_2$ levels are currently about 410 ppm and elevated $CO_2$ ($eCO_2$) levels are forecasted to rise up to 650 ppm by the year 2100. The global surface temperature increases by the end of the twenty-first century and is likely to exceed 1.5 °C. Climate change is likely to modify many critical virus epidemic components in different ways often resulting in epidemic, but sometimes may have the opposite effect, depending on the pathosystem and circumstances. Increasing global temperatures and elevated atmospheric $CO_2$ levels and the occurrence of water stress episodes driven by climate change have a dramatic effect on plant viral diseases, which alters the plant biochemistry and plant defence responses. It has a major impact on the diverse type of vector biology, feeding behaviour and fecundity, ultimately results in the transmission of plant virus diseases and the ease by which previously unknown viruses can emerge and leads to severe yield losses in many cultivated crops. Climate change is likely to diminish the effectiveness of some control measures of plant viral diseases. Fortunately, rapid advancing technological innovations currently underway in the world have the potential to provide many opportunities to improve the effectiveness of virus and vector control and they help to mitigate the impact of climate change on plant virus epidemics.

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**Keywords**

Carbon dioxide · Epidemics · Temperature · Virus

## 23.1 Introduction

Plant virus diseases are one of the important factors which have a direct impact on global agricultural productivity and climate change will further aggravate the situation. Climate change refers to a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer.

The main causes for climate change are volcanic eruption, rapid industrialization, the release of 28% of $CO_2$ from agricultural practices such as burning of paddy straw and other crop residues as well as enteric fermentation in domestic livestocks and livestock manure, then deforestation, resource extraction and pollution. Greenhouse effect is a natural process that keeps the Earth's surface warm; greenhouse gasses such as $CO_2$, $CH_4$, $NO_2$, ozone and CFC lead to the rise in temperature of the earth as well as atmosphere. Rising sea level, unpredictable weather patterns, land degradation, loss of wild life and biodiversity, drought, poverty, hunger and malnutrition are the main effects of climate change. Atmospheric $CO_2$ levels are currently about 410 ppm and elevated $CO_2$ ($eCO_2$) levels are forecasted to rise up to 650 ppm by the year 2100. The global surface temperature increases by the end of the twenty-first century and is likely to exceed 1.5 °C (IPCC 2014).

Plant pests and pathogens must evolve or migrate to survive climate change. Accelerated evolution prompted by a changing environment drives the development of variants potentially better adapted to the new conditions and changing geographic distributions bring together diverse lineages, thereby increasing diversity (Chackraborty 2013).

Plant hosts, vectors, and viruses are influenced by (1) the direct consequences of climate change, especially altered rainfall patterns, increased temperature, greenhouse gases, drought, and greater wind speeds, and (2) indirectly by things like regional alterations in areas cropped, ranges of crops grown, cultivation systems, distribution and abundance of vectors and weed or cultivated reservoir hosts. In turn, these factors influence the geographic ranges and relative abundance of viruses, their rates of spread, the effectiveness of host resistances, the physiology of host–virus interactions, the rate of virus evolution and host adaptation and the effectiveness of control measures.

The plant epidemic triangle illustrates the interactions between the environment, plant hosts and pathogens. Climate change can influence the environment from micro to macro scales (Fig. 23.1), thereby altering the disease triangle in different ways.

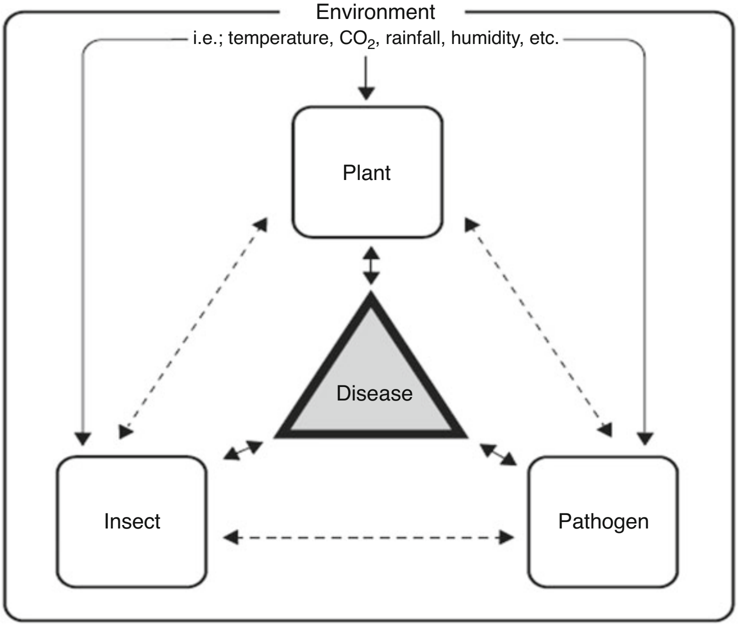

**Fig. 23.1** Illustration of the tripartite interactions (disease triangle) between plant, insect and pathogens influencing one another and by different environmental factors. Solid lines represent direct effects of elevated $CO_2$ ($eCO_2$); dashed lines represent indirect effects of $eCO_2$ changes via plant biochemistry or changes mediated through virus or insect vectors

## 23.2 Effect of Elevated $CO_2$ on Host, Vector and Virus

Ambient carbon dioxide ($aCO_2$) concentration has exceeded 400 ppm and future estimations predict an increase in up to 550 ppm within a few decades. Apart from the consequences that increasing $CO_2$ is the main driver behind climate change, it plays a major role in plant growth, physiology and metabolism as it is the direct substrate for photosynthesis. Among the observed effects on plants, typical responses to elevated $CO_2$ ($eCO_2$) include increased plant growth and biomass, canopy size, reduction in stomatal conductance and transpiration, improved water-use efficiency and higher photosynthetic rates. At the same time, increasing $CO_2$ alters the chemical composition of plant tissue with the accumulation of non-structural carbohydrates such as soluble sugars and starch and it also has an impact on the nitrogen cycle that results into a decrease in protein content and higher C/N ratio. The reduction in stomatal conductance may lead to a decrease in micronutrients such as calcium, magnesium or phosphorus due to the lower water uptake from the soil (Dader et al. 2016).

Elevated $CO_2$ alters insect herbivory by altering both the defence chemistry and signalling of plants and their nutritional and water contents, but the responses of herbivorous insects to these alterations are highly variable. It increases the production of salicylic acid but suppresses the production of jasmonates and ethylene, and these differential responses affect secondary metabolite pathways (Zavala et al. 2013). The indirect effects of $eCO_2$ on insect herbivores such as aphid, thrips and whitefly virus vectors include changes in their feeding, growth rates, fecundity and population density. These changes are mostly mediated by its effects on host plant quality including changes in host morphology, diversity, abundance, biochemistry, physiology and composition such as increased C/N ratios and altered concentrations of soluble and non-structural carbohydrates, starch and soluble proteins (Jones 2016).

Elevated $CO_2$ influenced different insect vector species in different ways. It had mixed effects on aphids which were highly species specific. With whitefly vector species it had no effect on *Bemisia tabaci* (sweet potato whitefly) but affected *Trialeurodes vaporariorum* (glasshouse whitefly) negatively. With thrips vectors it had little effect on populations of *Frankliniella occidentalis* (western flower thrips), but increased the population sizes of some other thrips vector species, whereas the population density of the nematode virus vector *Longidorus elongatus* in grass-dominated pasture was increased by $eCO_2$ (Yeates et al. 2003). However, sometimes the population densities of root-feeding Longidoridae in soil do not benefit from the increased root biomass that occurs with $eCO_2$. This may be due to factors such as enhancement of plant defence mechanisms against root-feeding nematodes or diminished availability of soil nitrogen under $eCO_2$ conditions (Cesarz et al. 2015).

### 23.2.1 Elevated $CO_2$ Impacts on Bell Pepper Growth with Consequences to Myzus persicae Life History, Feeding Behaviour and Virus Transmission Ability

Dader et al. (2016) investigated the effect of elevated $CO_2$ on bell pepper growth with consequences to *Myzus persicae* life history, feeding behaviour and virus transmission ability. Peppers grown under $eCO_2$ for 4 weeks were significantly taller although they had the same number of leaves than those under $aCO_2$. At harvest, leaf, stem and above-ground dry biomass were significantly higher under $eCO_2$. Leaf area was similar in both treatments but there was a significant decrease in specific leaf area under $eCO_2$. Exposure to $eCO_2$ did not alter carbon content; however, it significantly decreased foliar nitrogen content.

*Myzus persicae* pre-reproductive period, which was measured from aphid birth to adulthood, was 11% longer on pepper plants from $eCO_2$ environment. Additionally, under $eCO_2$, instars N3 and N4 lasted significantly longer than under ambient conditions. At the same time, the effective fecundity (Md) and offspring production over 10 days (M10) dropped respectively by 27% and 37% on plants grown under $eCO_2$. To understand the potential effects of increased $CO_2$ on virus transmission/acquisition efficiency, $CO_2$ was applied to receptor plants straight after aphid introduction (direct exposure). If the receptor plant had been previously grown under one of the $CO_2$ regimes before CMV inoculation by aphids (indirect exposure), a twofold decrease on CMV transmission was observed when source and receptor plants were grown under $eCO_2$ conditions compared to $aCO_2$.

The amount of foliar nitrogen in pepper was significantly lower under $eCO_2$ when compared to ambient conditions, which may well explain the poor aphid performance. Aphids which fed on plants grown under $eCO_2$ had a reduced efficiency, with an 11% longer pre-reproductive period and 37% fewer nymphs. This is probably mediated by reduced nitrogen content in the pepper source as aphids tend to be limited by the amount of nitrogen rather than carbohydrates. Under ambient $CO_2$ conditions, plant pathogens are responsible for triggering changes in nutritional quality or mediating attractiveness to increase the chances of vectors spreading viruses. The decreased CMV transmission found under $eCO_2$ may be associated with lower aphid attraction to virus-infected plants, resulting in fewer viruliferous aphids, which would ultimately reduce the spread of CMV under future climate conditions.

## 23.3 Temperature

Different species of host plants and virus vectors (insects, mites, nematodes and fungi) also have diverse temperature optima under which they flourish, some being adapted to warmer climates and others to cooler ones. Temperature is known to influence disease resistance to bacteria, fungi, virus and insects and different host-pathogen interactions respond differently to different temperature ranges (Garrett et al. 2006). High temperatures very often suppress plant immunity based on protein-protein, whereas low temperature impairs RNA silencing and plant defence against viral pathogen recognition (Zhu et al. 2010).

Temperature influences the insect herbivores by modifying their development, survival, fecundity, distribution and abundance. Considerable shifts in the distribution and abundance of insect vectors of plant viruses can result from small alterations in average temperatures. Increased mean temperature alters plant physiology by influencing secondary metabolite pathways, thereby altering the nutritious value of leaves to insect vectors. It increases stomatal conductance which influences the efficiency of photosynthesis. This alters virus multiplication within cells, thereby influencing virus systemic movement and acquisition by vectors. Increased mean temperature can increase the efficiency of virus transmission from infected to healthy plants by insect vectors. Such enhanced transmission efficiencies could enable viruses to expand their ranges to areas by transmitted effectively. However, distributions of some other viruses might contract from regions with increased temperatures due to diminished virus transmission efficiencies at higher temperatures. Also, prolonged heat waves can diminish vector numbers, thereby decreasing virus epidemics (Canto et al. 2009).

### 23.3.1 High Temperature Activates Local Viral Multiplication and Cell-to-Cell Movement of Melon Necrotic Spot Virus (MNSV) but Restrict the Expression of Systemic Symptoms

Kido et al. (2008) studied the effect of high temperature on *Melon necrotic spot virus*; a set of cotyledons of melon seedlings was mechanically inoculated with the sap of MNSV-infected melon leaves and an abrasive dust, carborundum. Then these inoculated seedlings were maintained at different temperature regimes such as 15, 20 and 25 °C, and the local and systemic expression of MNSV in melon plants was studied. They found that the expression of systemic symptoms increases as temperature falls from 25 to 20 °C and decreases as temperature rises from 20 to 25 °C. However, MNSV replication in melon cells and local viral movement within leaves following the inoculation of melon protoplasts or cotyledons were more frequent at 25 °C than at 15 or 20 °C.

The temperatures below 20 °C enhanced the systemic symptom development of MNSV; the degree of damage decreased gradually as the temperature increased and viral replication and spread increased above 25 °C. These necrotic symptoms at low temperature are due to viral systemic movement rather than the activities of local replication, whereas symptoms are often attenuated at high temperatures, a phenomenon also termed as heat masking.

### 23.3.2 Effect of Elevated $CO_2$ and Temperature on Pathogenicity Determinants and Virulence of Potato Virus X (PVX)/Potyvirus-Associated Synergism

Infections of plants by multiple viruses are common in nature and may result in synergisms. Several environmental factors influence plant-virus interactions and act on virulence and host defence responses. Mixed viral infections may be more frequent under environmental conditions which are associated with global warming.

Aguilar et al. (2015) studied the two main parameters behind global warming, carbon dioxide concentrations ($CO_2$) and temperature on pathogenicity determinants and virulence of potato virus X/potyvirus-associated synergism. Elevated $CO_2$ resulted in attenuated virulence of single infection by PVX, which correlated with a lower accumulation of virus. In contrast, virulence of PVX/potyvirus-associated synergism was maintained at elevated $CO_2$. On the other hand, elevated temperature decreased both virulence and virus titres in the synergistic infection.

Virulence of PVX was reduced in *N. benthamiana* plants grown under elevated $CO_2$, most likely influenced by a decrease in virus titres. These findings suggest that host plants may benefit from future higher atmospheric $CO_2$ through a reduction in damage caused by viral pathogens. It generally may be due to accumulation of more salicylic acid (SA) which induces the resistance to PVX in *N. benthamiana.* In contrast, virulence of the PVX recombinant expressing the HC protein from PPV and the synergistic pair PVX-PPV was maintained under elevated $CO_2$. Elevated temperature had a negative impact on both virulence and virus titres of the synergistic pair PVX-PPV, which implies that virulence was associated with virus accumulation to some extent. It has been reported that RNA silencing increases with increasing temperature and there is a general trend for symptom attenuation with high temperatures, even in viral infections expressing strong viral suppressors (VSR).

## 23.4 Rainfall

Shifts in precipitation have significant impacts on vegetation patterns with consequences for agriculture. Weather extremes result in excessive rainfall and flooding as well as severe drought. Such weather extremes can create exceptional conditions for extensive virus disease outbreaks in cultivated and natural vegetation. The increased frequency of heavy rainfall, extreme drought or flood events expected to arise from climate change are likely to influence plant virus epidemics in different ways. An increasing frequency of heavy rainfall events is likely to slow them by washing insect vectors like aphids, thrips and whiteflies off foliage, thereby diminishing vector populations. Waterlogging due to flooding kills pupal life stages of thrips vectors in the soil and oviposition of *B. tabaci* is impaired by heavy rain, so slowing epidemics of the viruses they transmit by reducing insect vector populations (Jones 2016).

Flooding within annual crop growing seasons enhances the subsequent growth of weed and volunteer crop plant reservoirs of viruses and arthropod vectors, and its occurrence outside growing seasons increases subsequent growth of such reservoirs. Prolonged drought stress on crop plants can limit arthropod vector population size and also restrict the size of weed and volunteer crop reservoirs of viruses and vectors. Both of these scenarios are likely to decrease virus epidemics by diminishing the arrival of viruliferous arthropod vectors in crops or native vegetation. Epidemics of fungus transmitted viruses are likely to become prevalent over wider areas because of greater vector zoospore activity stimulated by increased soil moisture. This would increase epidemics of furoviruses and bymoviruses of crops like cereals, potatoes and sugar beet. Drought-induced lack of soil moisture in fields inhibits both activity and movement of fungal vector zoospores as well as nematode vector, thereby preventing the spread of the viruses they transmit, but flooding would tend to have the opposite effect unless conditions become too anaerobic for their survival (Jones and Barbetti 2012).

### 23.4.1 Water Stress Modulates Soybean Aphid Performance, Feeding Behaviour and Virus Transmission in Soybean

Nachappa et al. (2016) studied the effect of water stress on soybean aphid performance, feeding behaviour and virus transmission in soybean. They analysed insect population growth, feeding behaviours, virus transmission and defence gene expression to characterize the mechanisms underlying the interaction between water stress, soybean aphid and aphid-transmitted, *soybean mosaic virus* on soybean plants. They constructed an experimental setup comprised of three stress regimes such as drought, well-watered and saturated and two levels of aphid infestation, i.e. viruliferous (infected with SMV) and non-viruliferous.

The population growth of non-viruliferous aphids was reduced under drought stress and saturation likely because the aphids spent less time feeding from the sieve element on these plants compared to well-watered plants. Water stress did not impact the population growth of viruliferous aphids. However, virus incidence and transmission rate was lowest under drought stress and highest under saturated conditions since viruliferous aphids took the greatest amount of time to puncture cells and transmit the virus under saturated conditions and lowest time under drought stress. Aphids did not benefit from improved phloem sap quality as indicated by their lower densities on drought-stressed plants. Drought and saturation had significant and opposing effects on the expression of marker genes involved in abscisic acid (ABA) signalling. Drought alone significantly increased expression of ABA marker genes, which likely led to the suppression of salicylic acid (SA)- and jasmonic acid (JA)-related genes. In contrast, ABA marker genes were down-regulated under saturation, while expression of SA- and JA-related genes was up- regulated. Apparent antagonism between ABA and SA/JA signalling pathways contributed to an increase in aphid densities under drought and their decrease under saturation.

### 23.4.2 Drought Reduces Transmission of Turnip Yellows Virus, an Insect-Vectored Circulative Virus

Michel et al. (2017) studied the effect of drought stress on the transmission of *Turnip yellows virus*, an insect-vectored circulative virus. A severe water deficit (WD) was applied to *A. thaliana* plants infected with a mutant of TuYV (TuYV-SUL) modified to induce vein clearing.

A negative effect of WD treatment on plant growth was observed. Three weeks after beginning of the WD, infected plant size showed a 30% significant reduction when compared to well-watered infected plants. At the end of the experiment leaf water content (WC) was about two times less in plants grown under WD compared to well-watered plants. In order to analyse the effect of water deficit on TuYV transmission by aphids, infected plants submitted to either WW or WD treatments were used as virus source in three independent transmission assays. Aphids were allowed to acquire the virus on infected plants for 24 h and then deposited on test plants grown under standard conditions (WW). Test plants were visually screened 3 weeks later for the development of vein clearing symptoms. Overall, the transmission of TuYV by *M. persicae* was reduced by 50% under WD compared to the transmission from TuYV-infected plants under WW conditions. Moreover, no difference in viral RNA accumulation was observed between plants submitted to WD or WW treatments. Interestingly, virus accumulation was significantly lower in aphids fed on plants under water deficit compared to aphids fed on WW plants (about 10 times less virus concentration in aphids fed on WD plants compared to

WW plants) which may explain the 50% decrease of transmission efficiency using aphids fed on WD plants.

Application of a severe water deficit to *Arabidopsis thaliana* plants infected with a mutant of turnip yellows virus (TuYV, family Luteoviridae) triggers a significant alteration of several plant phenology traits and strongly reduces the transmission efficiency of the virus by aphids. Although virus accumulation in water-stressed plants was similar to that in plants grown under well-watered conditions, the alteration of the aphid feeding behaviour on plants under water deficit results in reduced accumulation of virus in aphids fed on plants under water deficit.

### 23.4.3 Epidemiology of ChiLCVD on Syngenta 5531 Chilli Hybrid

Manjesh (2018) studied the influence of weather parameters on ChiLCVD incidence and whitefly population was carried out for hybrid Syngenta 5531 in natural field conditions.

Epidemiological study showed that environmental factors have a significant impact on the leaf curl disease development and whitefly population. The correlation of maximum temperature with whitefly population was highly significant. A strong positive correlation exists between the whitefly population and maximum temperature; it means that with the increase in maximum temperature, whitefly population increases. As the maximum temperature increases from 29 to 37 °C, the whitefly population gradually increases. The relationship between the whitefly population and minimum temperature showed a slightly low positive correlation. It means that with the increase in minimum temperature whitefly population increases. As the minimum temperature increases from 14 to 22 °C, the whitefly population gradually increases. A strong negative correlation exists between relative humidity I (RH I) and whitefly population. As the RH I increases from 52 to 89 (%) the whitefly population goes on to decrease. So, it resulted in a decrease in whitefly population for all the three hybrids.

Similarly as RH I, a strong negative correlation exists between relative humidity II (RH II) and whitefly population. As the RH II increases from 30 to 52 (%) the whitefly population goes on to decrease. The relationship between whitefly population and sunshine hours was correlated. Sunshine hours were ranged between 0.227 and 0.556. The results showed that a slightly positive correlation exists between the whitefly population and sunshine. It means that with the increase in sunshine hours, whitefly population increases. A strong positive correlation exists between the whitefly population and evapotranspiration. The results of correlation showed that, as the evapotranspiration increases from 3.7 to 9.4, whitefly population increases. The relationship between the whitefly population and wind speed (km/h) showed a slightly low positive correlation between the whitefly population and wind speed in all the three hybrids, respectively. As the wind speed increases from 3.4 to 7.4 (km/h), the whitefly population increases gradually.

The results of correlation analysis between whitefly population and ChiLCVD incidence showed that a strong positive correlation exists between the whitefly population and ChiLCVD incidence. It means that with the increase in whitefly population, ChiLCVD incidence increases. Positive correlation of maximum temperature and whitefly population resulted in an increase in whitefly population. Very low positive correlation of maximum temperature and disease incidence resulted in a slight increase in disease incidence. A positive correlation of minimum temperature and whitefly population exists; however, the decreasing minimum temperature from 48th SMW to 52nd SMW resulted in a decrease in whitefly population. The negative correlation of relative humidity and whitefly population suggested that the increasing relative humidity resulted in a decrease in whitefly population, whereas declining relative humidity favoured the whitefly population. The negative correlation of relative humidity and disease incidence suggested that the increase in relative humidity favoured the decrease of disease incidence.

*Mungbean yellow mosaic virus* (MYMV) causes yellow mosaic disease in pulses, which is the most serious disease in greengram, blackgram and many pulses growing in the areas of North Eastern Karnataka region. The reasons for its higher incidence can be due to epidemiological factors. Whitefly population was greatly influenced by environmental factors; the least whitefly population was observed during 40th SMW (16/trap) and 39th SMW (20/trap) when the weekly mean maximum temperature was 28.9 and 30.4 °C, minimum temperature was 22.8 to 22.2 °C and total weekly rainfall was 60.8 mm for 4 days, respectively. The highest number of whiteflies was noticed during 50th SMW (1456/trap) when maximum temperature was 29.7 °C, minimum temperature was 16.7 °C and rainfall was 8.2 mm. This indicates that the decrease in whitefly population was mainly due to higher rainfall and lower minimum temperature, whereas the increase in whitefly population was due to higher maximum temperature and no rainfall. Results revealed that there was a negatively significant correlation between whitefly population and minimum temperature ($r = -0.354$) and positive significant correlation with maximum temperature ($r = 0.250$). The correlation of whitefly with rainfall was negatively significant ($r = -0.456$), while other factors like relative humidity (minimum and maximum), sunshine hours and maximum wind speed showed nonsignificant correlation with whitefly population. Sunshine hours recorded showed positive relation with whitefly population ($r = 0.631$). Regression analysis showed that all these weather factors were found to contribute up to 69.6% towards the whitefly population (Meti and Kenganal 2018).

### 23.4.4 Pigeon pea Sterility Mosaic Disease

The disease is caused by pigeon pea sterility mosaic virus (PPSMV) transmitted by eriophyid mite *Aceria cajani*. The reason for increased epidemics of SMD in recent years in Northern Karnataka mainly in Bidar and some talukas of Gulbarga could be due to the continuous cultivation of susceptible varieties over large areas, as a sole crop year after year in the same fields. The practice of leaving stubbles (30–60 cm height above ground surface) after harvesting the crop in the field allows new flushes of growth, especially in plants under the shade of sugarcane fields and near irrigation channels. Such plants supports mite multiplication and serve as volunteer inoculum sources for new pigeon pea crop sown the following season (Dharmaraj et al. 2004).

The severity of sterility mosaic disease of pigeonpea in North Eastern Karnataka was assesed and incidence varied from 9.50 to 23.50%. Bidar district recorded the highest incidence of the disease (26.38%) followed by Kalaburagi (24.08%), and the least incidence was at Yadgiri (10.81%). The highest incidence of 23.50% was recorded at the Rajgira village of Bidar Taluk (Amaresh and Naik 2017).

The average temperature of about 20–30 °C and 61.3% and 64.3% of relative humidity was congenial for the multiplication of mite. But very high temperature is not suitable for the growth of mite. Heavy rainfall is also not suitable for the growth of mite. Wind velocity is also a very important factor responsible for the spread of disease. The severe mosaic affects the plant height and branches of the pigeon pea plants. Disease severity was high in the early stage of infection causing severe mosaic disease where flower and pod formation ceased resulting in complete crop failure (Dipshikha et al. 2013).

## 23.5 Conclusions

Increasing global temperatures and elevated atmospheric $CO_2$ levels and the occurrence of water stress episodes driven by climate change have a dramatic effect on plant virus diseases, which alters the plant biochemistry and plant defence responses. It has a major impact on the diverse type of vector biology, feeding behaviour and fecundity, ultimately results in the transmission of plant virus diseases and the ease by which previously unknown viruses can emerge and leads to severe yield losses in many cultivated crops. Climate change is likely to diminish the effectiveness of some control measures of plant viral diseases. Fortunately, rapid advancing technological innovations currently underway in the world have the potential to provide many opportunities to improve the effectiveness of virus and vector control and they help to mitigate the impact of climate change on plant virus epidemics.

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# 24

# Adaptation Strategies for Protected Cultivation Under Changing Climate Patterns in Dry Regions

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**Abstract**

Climate change (CC) is the main obstacles being faced by mankind throughout the entire world. Majority of the agricultural sector is harmed not only by the biotic factor like pests and diseases but also due to a rapid decline in the supporting environment due to climate change because of its less publicity. Dry land ecosystems are mainly grasslands which have special strategies for handling climate change. Rural people are much prone to changes in the climate and thus there is a need to introduce adaptation strategies in protected cultivation in dry regions. New implementations have been developed by adjusting the human and natural systems to their response to climatic factors; manipulating the experiments; making the temperature to fluctuate; checking the responses created by plants through a long observation; changing the crop pattern, new varieties, novel insecticidal treatment, and sowing techniques; etc. Due to a lack of improved technology, less training, and signs of warnings in climate change, there are constraints in adaptation strategies. Hence, the much-needed information relating to the climate patterns especially in dry regions must be organised in order to fulfil farmer's adaptive approaches against climate change.

**Keywords**

Climate change · Dry land · Adaptation strategies · Protected cultivation

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## 24.1 Introduction

Climate change (CC) is the most challenging issue nowadays as it has long-term effects and causes grief to mankind worldwide. Most of the time agriculture is hampered by the change in climate causing low yields and insect pest proliferation and in long run the productivity of the food is declined. Climate change quickens land degradation which is known as dry land. Dry land is generally the ecosystem which consists of grassland, rangeland, and woodlands which covers about 40% of terrestrial surface (IUCN 2019). In dry land, water scarcity is the main obstacle faced by the people, which is reported to further increase due to climate change, the growth of demographic variables, and the change in land cover (Hassan et al. 2005; UNCCD 2017). Scientists stated that the areas of dry land will get increased by 50% globally by climate change by 2100 (Huang et al. 2015). Rural people are much prone to change in the climate as they are mostly dependent on agriculture which affects their livelihood like crop decline, livestock failure, decreasing marine resources, decline of forest products, and outbreaks of diseases and pests (Molnar 2010). Rural people faced the risks more in climate change due to high poverty, more population, ethnic tensions, insecurity of food, and instability of political order (Misselhorn 2005; Reynolds et al. 2007; FAO 2009, 2018). Due to climate change, the introduction of adaptive strategies in development sectors is needed (World Bank 2010). The adaptive strategies should be sustainable and eco-friendly and should be easy for farmers to adopt economically (ATPS 2013). Adaptation to climate change signifies adjusting the human and also natural systems to their response to the climatic factors and experimental manipulation which balances the harm or utilisation of good opportunities (IPCC 2001). UKCIP (2003) also explained adaptive strategies as "a process which includes risk of harm and also realization of benefits connected with climate change and climate variability". Adaptation strategies is a strategy of finding the information and conditions related to the impacts of climate change and the major factors in which people find it difficult to adopt, decreasing their vulnerability and making them ready for environmental hazards (Khajuria and Ravindranath 2012). Because of the changing climate scenario and its adverse effects, protected cultivation is being introduced with different adaptive strategies to combat change of climate at the farm level. Protected cultivation provides a microclimate to crops, giving them a friendly environment to either fully or partially control their growth period (Mishra et al. 2010). Individual plant species needs different protected cultivation like net houses, greenhouses, and tunnels which helps the plants to decrease yield loss due to extreme climate condition and gives them protection from several diseases, weeds, and pests, allowing for crop quantity and quality improvement and productive resources and expanding farmer's income (Ummyiah et al. 2017). Most of the time, protected cultivation is used for vegetables, flowers, and fruits as they are more unsafe to variability of climate and extreme climate (Knox et al. 2010; Choudhary et al. 2015). Adaptation strategies are indispensable as they reduce the adverse effects of climate change, but due to a lack of much-needed information relating to climate change patterns, high cost of adaptation procedures, and less training and signs of warnings in climate change, farmers are facing major problems. Usually they faced several problems while adopting the adaptive strategies to climate change which cannot fulfil the adaptation approaches. Therefore, improved technology and strategies which will strengthen farmers' adaptive approaches against climate change are needed.

## 24.2 Need for Adaptation Strategies Under Protected Cultivation in Dry Regions

Adaptation implies the ability of a system to adjust to climate change (including climate variability and extremes) and to moderate potential damages, to take advantage of opportunities, or to deal with the consequences (IPCC 2001). Climate change is more visible in recent decades, resulting in heightened awareness of the phenomena. The high temperature and drought events are becoming more often because of climate change, putting agriculture in arid regions at risk (Giorgio and Lionello 2008; IPCC 2014). The unpredictability of water in semi-arid zones will be unsafe for crop productivity and also create socio-economic effects (Polade et al. 2017). Crop adaptations (in protected structures) in the cropping systems are the approaches or practices which are employed particularly on the agricultural field and will be required to tackle the susceptibility of dry regions to climate change. Anticipated climatic changes encourage the expansion of protected agriculture, i.e. greenhouses and screenhouses, within which external climatic effects are restrained. According to Boulard et al. (2011), non-protected agriculture or natural systems such as forests and pastures are thought to be more climate-dependent than protected ones. However, even if protected farming were less dependent on local climate circumstances, it would still be a reason for concern because internal climate and energy balance and thus economic models are heavily influenced by external factors. Various approaches and technologies are accessible for improving adaptation of crops in the farm level to climate change. Subsequently, scientists started to produce climate models, both regional and global, to obtain an insight into future changes. The results obtained serve nowadays as a basis for decision-makers and scientists to create adaptation strategies for use in the future. The model changes are an increasing global mean temperature, an increase in atmospheric $CO_2$, and more extreme climatic factors such as heat waves (IPCC 2013).

The adaptation strategies comprise of genetic improvement by providing new cultivars which have a high potential for yield, adapting to water scarcity and high temperature, adopting agronomic practices which are efficient in irrigated as well as rainfed areas, discovering symbiosis between microbes and plants, and producing vegetation which can endure abiotic stress (Araus et al. 2008; Borras and Slafer 2008; Lehmann et al. 2013; Bodner et al. 2015; Dessaux et al. 2016). Based on farm level, the adaptation strategies consist of dealing with the farmer's behaviour for implementing new practices and also economic incentives. Leafy vegetables which require continuity of supply are particularly vulnerable to extreme weather events. Normally these crops rely on a combination of successional plantings and appropriate genotypes for reliable scheduling. Greater fluctuations in temperature may result in a compression of harvest dates (Collier et al. 2008). Climate change affects crops in various ways, so adaption with new strategies to overcome the impacts of climate change is very much important. By 2100, majority of climate models have forecast a sudden decrease of precipitation and rise in temperature (Giorgio and Lionello 2008; García-Ruiz et al. 2011; Williams 2017). Scientists also reported that winter precipitation frequency will also decrease and rainfall will increase in some areas (Polade et al. 2017). The constraints faced in the environment due to climate change would reduce the crop yield as well as the quality of crop and in addition it will affect the planted area of several crops (Challinor et al. 2014; Lesk et al. 2016).

## 24.2.1 Impacts of Climate Change

### 24.2.1.1 Increase in Atmospheric $CO_2$

$CO_2$ is predominantly released into the atmosphere because of the combustion of fossil fuels. After burning, this carbon is released into the atmosphere, with only a small chance of being re-sequestered, resulting in an accumulation of greenhouse gases ($CO_2$, $CH_4$, $N_2O$) and subsequent warming due to the greenhouse effect. $CO_2$ levels in the atmosphere are predicted to rise to between 442 and 540 parts per million by mid-century (IPCC 2013). Increased $CO_2$ concentrations may be beneficial for agricultural productivity, particularly the summer and depending on the current climate scenario.

### 24.2.1.2 Increase in Air Temperature

Since climate change is generally associated with globally increased air temperature, it may support to cultivate new crop species, a higher crop production, and an increase of proper areas for crop cultivation in northern areas. However, in southern areas some disadvantages may predominate. The possible increase in shortage of water and extreme weather conditions will probably cause higher as well as lower yield variability and lessen the areas producing traditional crops (Olesen and Bindi 2002). In our opinion, this statement could be generally applied for warmer regions worldwide, even if the local climate specifics and particularities must be considered. Since climate changes will be associated with generally higher temperatures, it is safe to assume that this trend of increasing area of simple greenhouses with a passive control of environmental conditions will continue in nations with mild winter climates in the nearby future (Montero et al. 2009). Unforeseeable climate events and consumer requirements for all year-round ornamental plants and health-promoting plant compounds from fresh vegetables will enhance the trend of intensive cultivation in temperate areas as well (Gruda et al. 2019).

### 24.2.1.3 Change in Rainfall

Due to the consequences of climate change, the spatial distribution of rainfall in some areas is changing, resulting in water shortages. Because irrigated horticulture needs plenty of water, there will be increased rivalry among water users in the future (Bisbis et al. 2018a, b). Plants will undergo drought stress if growers fail to maintain proper irrigation due to water shortages, which could result in crop failure (Gruda et al. 2009).

#### 24.2.1.4 Instability in Yields of High-Quality Products

On account of the problems in greenhouse climate control, adaptive measures will be required to provide stable yields of excellent product quality. In this scenario, manufacturers must invest in improved technology that decreases wastage by lowering the percentage of unmarketable yield and boosting the level of sugars, vitamins, and antioxidants in their products. The market expects a flawless product that is also safe to eat. This puts vegetable producers under a lot of stress since they have to meet market and consumer needs while climate circumstances are deteriorating. Water conservation, for example, would become a key factor in cultivation tactics such as the use of shading screens to mitigate climate change consequences such as increase air temperatures and water scarcity.

#### 24.2.1.5 The Impacts of Elevated Temperatures on Pests and Diseases

Changes in the climatological framework will affect not just vegetable harvests but also insect pest life cycles and reproduction rates. Winter death rates of insects will decrease as global temperatures rise, allowing for earlier infestations and more generations per year, such as aphids, along with the introduction of new species, e.g. *Tuta absoluta* (Van Damme et al. 2014; Bisbis et al. 2018a). Increasing $CO_2$ levels in the atmosphere have an effect on plant-insect interactions by changing the host plant's food quality, which either reduces insect health or increases infestation severity, depending on the species involved (Dader et al. 2016). Warm winter temperatures usually result in increased crop transpiration rates and reduce the vapour pressure deficit (VPD) in the greenhouse. High winter precipitation with more humid days would exacerbate the situation. This winter pattern highlights the need for better greenhouse humidity control in the future to avoid phytosanitary issues including mildew, *Botrytis*, and grey mould. The installation of insect-proof screenhouses may help to increase water efficiency while also lowering pesticide application, which has become increasingly important for consumers who prefer pesticide-free products (Bisbis et al. 2018a).

## 24.3 Different Adaptations Strategies for Protected Cultivation to Reduce the Climate Change Effect in Dry Regions

Extreme weather condition for instance heat waves and drought periods will become more often because of climate change, and a corresponding overall increase in air temperature during the winter may provide new opportunities. Here we describe the benefits and drawbacks of several adaptation strategies for dealing with the issues posed by the effect of climate changes.

### 24.3.1 To Combat Climate Change, Greenhouse Gas Emissions Must Be Increased

The framework conditions in agriculture will change due to global warming and preserving crops from poor weather conditions will become a crucial concern for adaptation. Extreme weather, such as wind or hail storms, is protected by the structure and cover, which also makes it easier to control environmental parameters like temperature, humidity, and radiation. Greenhouses provide excellent chances to control indoor climate conditions and become less reliant on the outside environment. This is a significant advantage over open-field production and a valuable tool for dealing with climate change issues. It's especially relevant for hot climates like the Caribbean (Lawrence et al. 2015) and Africa (Abukari and Tok 2016; Schreinemachers et al. 2018), where a controlled environment was regarded as a promising adaptation approach for limiting climate change effects. Controlled environment agriculture, according to Lawrence et al. (2015) and Schreinemachers et al. (2018), contains inherent qualities that reduce some of the abiotic and biotic challenges to agricultural production in a changing environment. Structural designs, roof and side coverings, and growth methods are among the features that protect the crops from unfavourable weather conditions, maximise the use of inputs (particularly land and water), and result in higher yields per unit area (Lawrence et al. 2015). Furthermore, even on non-productive lands, year-round and high-quality vegetable crops might be grown with a significant reduction in the quantity and amounts of agrochemicals utilised. Nonetheless, greenhouse structures may need to be modified to accommodate new climates. Their construction has a significant impact on the indoor climate. Many greenhouses in Germany are over 25 years old (Gruda et al. 2009) and lack the requisite temperature control capabilities for a more harsh environment. Because of the low ridge height in these structures, heat builds up quickly in the summer, causing plants stress (Von Elsner et al. 2000). The buoyancy effect causes hot air to ascend above the crop environment because of the ridge height of modern buildings (5–6 m or even 8 m). This provides a better temperature buffer during hot periods, but it consumes more energy to heat during cold periods. High buildings also provide more room for climate control technology, which will be required to maintain effective temperature control as the world warms (Von Elsner et al. 2000). However, placing such equipment beneath the roof and above the plants provides shadowing, which is normally undesirable in northern climates.

### 24.3.2 To Reduce Water Scarcity, Water Consumption Must Be Reduced and Water Usage Efficiency Must Be Increased

Climate change scenarios forecast more frequent occurrences of extreme conditions, such as drought years, along with an uneven distribution of precipitation throughout the year, requiring increased irrigation efficiency. Increasing the efficiency of water use and protecting crops from harsh weather conditions are two significant adaptation challenges. Screenhouses, naturally ventilated greenhouses, semi-closed greenhouses, and closed greenhouses are described in detail below.

#### 24.3.2.1 Screenhouses

The usage of shade screens is proven to lower atmospheric water consumption while also allowing for increased water efficiency (Tanny et al. 2015). As a result, it could be a viable strategy for dealing with the negative consequences of climate change. Tanny et al. (2009) found that during the daylight, VPD fell beneath the screens, which shows that the air was more humidified by the lower air exchange rate expected beneath the screen. Similarly, when a pepper crop was shaded by a shading screen cover, the screenhouse air provides more humidity in comparison to the outside air most of the time (Moller and Assouline 2007). Kittas et al. found that the VPD of shaded plants was 50% lower in comparison to unshaded plants. The increase in air humidity and thus the associated decrease in the vapour pressure deficit may reduce the orchard's irrigation demand, resulting in water savings, which is a significant benefit in changing climate and the frequent occurrence of drought (Siqueira et al. 2012).

Screens reduce VPD (i.e. increase air humidity), but their effect on air temperature is complex and dependent on other factors, most notably ventilation rate. Through the Penman-Monteith equation, the four microclimatic variables of solar radiation, wind speed, air humidity, and air temperature, as well as additional plant and soil properties, determine crop evapotranspiration (Allen et al. 1998). As a result, growing crops under screens may reduce evapotranspiration due to the effects of the screens on the microclimate. Pirkner et al. (2014) demonstrated that crop evapotranspiration under a light shading screen was 66% of evapotranspiration of a similar crop estimated under outside climatic conditions in the same region for a table-grape vineyard covered by a light shading screen. As a result, this study suggested a potential water savings of more than 30%. According to a sensitivity analysis (Haijun et al. 2015), the reduction in evapotranspiration is primarily due to the effects of the screen on radiation and wind speed. Farmers are interested in water use efficiency (WUE), which is the yield obtained per unit of irrigation water, in addition to water savings through reduced evapotranspiration. As a result, low-cost structures such as screenhouses and naturally ventilated greenhouses may improve water efficiency. Aside from adjusting the crop environment to climate change situations, screens may minimise greenhouse gas emissions, so directly contributing to future climate change reduction.

Growing in a greenhouse, like growing in a screenhouse, can save water because of reduced wind speed and elevated humidity under the cover, resulting in less evaporative demand and thus crop transpiration (Stanghellini 1992). This environment provides an excellent opportunity to transition from soil to soilless culture systems and increases water use efficiency even further, particularly in recirculating systems that recapture drain water for reuse (Gruda 2009). In addition, the lack of bacterial activity in some growing media reduces CO2 emissions when compared to open-field production (Hashida et al. 2014).

#### 24.3.2.2 Semi-/Closed Greenhouses

Despite lower summer precipitation in Europe, ensuring adequate water supply is critical for vegetable production. Longer drought periods during the main growing season will necessitate a more efficient and sustainable use of water resources, in addition to ensuring adequate total amounts of water (Bisbis et al. 2018a). Due to the reduced opening of ventilation windows in closed and semi-closed greenhouses, transpiration is reduced by the overall higher RH of around 75–85% (Dannehl et al. 2014). Reduced water consumption increases water use efficiency (WUE) of up to 71% (Dannehl et al. 2014). Another intriguing aspect is the ability to capture and recycle the water transpired by plants in the nutrient solution. Up to 85% of the total irrigation water condenses on the heat exchangers during the air cooling process and can be added to the nutrient solution without concern (Teitel et al. 2012). With both a reduction in total water consumption and the recycling of transpired water, future water shortage challenges can be effectively mitigated without sacrificing productivity or quality (Van Kooten et al. 2008). Finally, water conservation and increased water use efficiency in screens and naturally ventilated greenhouses are critical for delivering food during drought years or when precipitation levels vary and do not correspond to the cropping season. Such structures require little capital commitment on the part of the farmer, as they are cost effective in underdeveloped nations where high-tech greenhouses are out of reach. Only high-tech greenhouses with very significant investment costs should employ semi-/closed greenhouses. The overall greater relative humidity in such structures reduces transpiration due to the restricted opening of ventilation windows. Water use efficiency improves due to lower water consumption and the ability to extract water from greenhouse air.

### 24.3.3 For Winter Production, Increased Usage and Improvement of Natural and Extra Light

The greatest constraint to growing crops in winter in Western Europe is the lack of sunlight and cold temperatures. Cloud cover may intensify in the future as climate change increases winter precipitation, resulting in even more shade. To take use of the increased warmth given by climate change, maximising light within the greenhouse will become increasingly vital in the future. The structure and cover of the greenhouse have a significant impact on light transmission. The amount of light that reaches the crop is greatly influenced by architectural design, orientation, and the type of the cladding material. Teitel et al. (2012) discovered that the greatest reduction in radiation occurred around midday, in the area beneath the roof openings. Light transmission is better in the winter when the greenhouse is aligned east-west; however, light transmission is better in the summer when the greenhouse is aligned north-south (Von Elsner et al. 2000; Kempkes et al. 2015).

Cover materials, both plastic films and glass, are constantly improving their optical characteristics. Any major improvement in light transmission is mostly dependent on advancements in transparent roof materials (Bakker et al. 2008). In the greenhouse business, numerous anti-reflex coatings have recently been introduced. They improve light transmission to some extent. Double-sided coated anti-reflex glass (Hemming et al. 2006), micro-V treated glass (Sonneveld and Swinkels 2005), and triple-layer systems are also promising alternatives (Bot et al. 2005; Bakker et al. 2008). Improving greenhouse light transmission benefits photosynthesis while also lowering the amount of supplemental heating electricity required during the winter, improving energy efficiency (Elings et al. 2005).

The winter-light greenhouse concept was created in the Netherlands, with wider windows, diffuse glazing with an anti-reflection coating, specific energy screens built for high light transmission, and a white coating for construction parts to improve light reflectance (Hemming et al. 2017). When compared to traditional greenhouses, this design enhanced light transmission by 12% in the winter (Kempkes et al. 2015). Artificial lighting has become a prevalent practice in the endeavour to achieve year-round output (Bakker et al. 2008). Artificial light was first used on floriculture crops such as chrysanthemums and roses, but in the last decade, it has also been used on fruits and vegetables (Bakker et al. 2008).

### 24.3.4 Heat Waves and Required Cooling

It is useful to draw lessons from natural processes while coping with natural extremes. Microclimatic effects caused by forest canopy closure can buffer biotic responses to macroclimate warming driven by CC, according to a study of understory canopy in a forest. The rise in the presence of warm-adapted species was mitigated in forests with denser canopies, which is possible because of higher shade and colder growing-season ground temperatures. As a result, the forest trees' canopy closure induced natural shade in a similar way as an artificial shading screen. Providing fruit orchard shading by porous screens can reduce noontime air temperature by 1–2 °C (Tanny et al. 2009), which may be the most important factor in preserving great fruit quality in changing climates. It may be possible to solve concerns with supply continuity owing to CC by switching to varieties with different temperature requirements for green crops (Collier et al. 2008).

#### 24.3.4.1 Cooling and Ventilation by Screens

Air temperature and humidity were monitored within the trees' foliage in a field experiment in an apple orchard covered with screens of various shade levels (0, 16, 30, and 60%, where 0 is control without shading). The cooling impact increased with the shade level, and the air temperature under the screen was lower by around 1.4 °C at noon (Tanny et al. 2009). This drop in daytime air temperature could have a substantial impact on fruit quality, especially during intense heat waves, which are more common under climate change conditions. The air temperature in the screened treatments increased somewhat at night, by around 0.3 °C, by reducing radiative cooling. Because of the good yields and water reserves, cultivating banana orchards beneath light shade screens has become standard in Israel (Dicken et al. 2013). Air temperature was reduced by 1% and relative humidity increased by 8% in a banana screenhouse when compared to a nearby external meteorological station, according to measurements (Haijun et al. 2015). The lower ventilation in the banana screenhouse, with side walls, and the apple orchard, which was covered by a shading screen cover on the roof only, with no sidewalls, and presumably was much better ventilated, is attributed to the small change in air temperature as compared to that of the abovementioned apple orchard. Moller and Assouline (2007) found that the indoor air temperature was lesser than the outside temperature most of the time in a shading screenhouse (30% black shading screen) covering a pepper crop. They discovered that the air temperature under the screen was approximately identical to that outside, and the leaf temperature of shaded leaves was roughly lower by 5 °C than that of exposed leaves. They pointed out that the screen was only installed on the roof, allowing for adequate ventilation and balancing the inside and outside air temperatures. The most noticeable consequence of screens is that they only transmit a fraction of sun radiation. They also convert a portion of the direct radiation to diffuse, which may improve photosynthesis in huge plants with a lot of shaded leaves.

#### 24.3.4.2 Cooling in Passively Ventilated Greenhouses

The microclimate in naturally ventilated greenhouses is determined by the kind and geometry of the greenhouse, and it can be modified by opening and closing the vents. The reduction of internal temperature and humidity due to ventilation increased with the height of the window opening and wind speed, but decreased with solar radiation, according to the findings. On hot sunny days, technologies to cool greenhouse air have become more vital, notably natural ventilation systems, which use far less energy than fan ventilation systems. In mild winter regions, natural ventilation systems in greenhouses consist of either roof or side windows, or a combination of both. The windows can be opened or closed depending on the desired indoor microclimate and outside weather conditions. The ventilation method used is determined by the climate, crop, and structure type. For example, side ventilation is ineffective in particularly large greenhouses; hence, ventilation is mostly relied on roof vents. Bournet et al. (2007) utilise computational fluid dynamics techniques to optimise the location and distribution of apertures over the greenhouse cover. These tools allow modelling of the ventilation rate under various conditions. Such simulations can also anticipate the internal geographical distribution of air temperature at the canopy level, a variable that is critical for crop yield, particularly in changing climates. Cooling solutions based on wet pad (Kittas et al. 2003) or fogging (Arbel et al. 2003) are employed if natural ventilation is insufficient to achieve the appropriate internal air temperature.

#### 24.3.4.3 Air Velocity and Ventilation Rate Are the Main Features to Efficient Passive Cooling

Screens impose, or drag, resistance to air flow due to the distortion of streamlines around the screen threads. This, in turn, reduces the air velocity under the screen and the ventilation rate or exchange rate between the inside and outside air temperatures. Tanny et al. (2006) have reported the measurements of air velocity at 5 m height in a banana screenhouse and showed that the internal ($u_{\text{in}}$) and external ($u_{\text{out}}$) relation between of air velocity was $u_{in} = 0.6\ (u_{out} - 0.18)$, $R^2 = 0.89$. In a soybean field covered by a shade cloth, Allen (1975) reported a reduction of 67% in air velocity, i.e. $u_{in} = 0.33\ u_{out}$. Reducing air velocity is an advantage in high wind speed region which may cause damage to leaves and yield. Air exchange rate is an important parameter for protected cultivation; sufficient exchange is essential for adequate supply of $CO_2$ for plant photosynthesis and for the removal of excess heat and water vapour from within the structure. For a large banana screenhouse Tanny et al. (2006) compared their results with the volume flow rate of a pepper screenhouse (Tanny et al. 2003), as well as with the flow rate obtained by Demrati et al. (2001) in a naturally ventilated banana greenhouse. The flow rate in the banana screenhouse was much larger than those in the banana greenhouse and the pepper screenhouse. This result clearly shows the effect of the screen permeability on air exchange rate. A numerical simulation by Teitel and Wenger (2010) showed that not only the screen type and porosity affect internal air velocity but also the structural shape of the roof. In particular they have shown that pitched screened roofs with inclinations of 22° and 33° induced a larger air exchange rate through the screenhouse than flat roofs. Boulard et al. (1997) investigated ventilation in six types of naturally ventilated greenhouses and tunnels. Using neural network analysis, they have shown that ventilation rate is mostly affected by the area of openings and external wind speed.

#### 24.3.4.4 Semi-closed Greenhouse Cooling and Efficient Use of $CO_2$

The heart of the system is cooling. The semi-closed greenhouse is a powerful tool to technically control the crop environment, allowing a higher degree of climate control. Hemming et al. (2006) reported about the use of the greenhouse as solar energy collector based on the principle of heat storage and heat pump system and an efficient heat exchanging system near the crop. A number of technical devices can be used to realise climate control in the semi-closed greenhouse. The concept by Qian et al. (2009) was reported to be based on a system that removed the warm and moist greenhouse air by forced ventilation to be cooled in air treatment units (ATU) based on heat exchangers. The ATU served as a dehumidification unit because vapour condensated on the cold heat exchanging surface. After the air conditioning process, fresh air is returned to the crop. It was shown that cooling from above does not induce vertical temperature gradients while cooling from below traps the cold air on the bottom of the greenhouse due to density gradients. All technical improvements that reduce the ventilation requirement of the greenhouse could have the capability to limit the natural inflow of carbon dioxide, thereby limiting photosynthesis and reducing yield (Montero et al. 2009). This technology is most likely to be profitable also in simple greenhouses and the injection rate must be linked to the ventilation opening. Since $CO_2$ concentration will be increased in the future due to climate change, a balance with the outside concentration can be reached through the injection of outside air. This is the “wise use” of $CO_2$ in greenhouse production without high-cost investments.

### 24.3.5 Plant Protection in a Changing Climate

Qian et al. (2009) observed yield reductions in tomato, due to *Botrytis* mould, during the growing season, but without correlation to high humidity. RH was similar or even lower to that in the control, where plants remained healthy. The incidence of diseases and pests can be enormously lowered through the use of protected cultivation systems. Such systems enable producers to gain more control over their production environment (Schreinemachers et al. 2018). However, even though greenhouses are protected environments, pests and diseases can still manage to enter through ventilation windows or other openings. Closed greenhouses appear to be a suitable solution for this issue because windows remain sealed. This was confirmed by Opdam et al. (2005), who showed that tomato production is possible with an 80% decrease in chemical plant protection. However, due to high cooling investment and running costs, the trend is rather towards semi-closed greenhouses, where window opening is only reduced, but allowed. Thus, these greenhouses should include insect screens installed on the windows to prevent pests from entering, while guaranteeing sufficient air exchange (Teitel 2007). Apart from the openings, the climate conditions within the greenhouse can favour the spread of diseases and pests in the crop if the environment is not managed properly. High relative humidity may result in fungal diseases such as *Botrytis*, especially when droplets form on the leaves of the crop (De Gelder et al. 2012).

### 24.3.6 Breeding

Crop breeding is an adaptive response to change in climate for using both traditional and biotechnology techniques that allow the introduction of resistant crop varieties. Bindi and Howden (2004) stated the selection of cultivars with appropriate thermal time and vernalisation requirements, heat shock resistance, drought tolerance, high protein and nutritional levels, and resistance to new pests and diseases. It is essential to preserve high irrigation efficiency in reduced water supply conditions. In our opinion, this will be necessary for plastic houses or tunnels without climate control facilities; breeding of fruit vegetable cultivars with higher productivity and a low biomass will help to maintain irrigation efficiency. According to Lankhorst (2017), on average, crops convert only 0.5% of incident sunlight into biomass, whereas some wild plants convert sunlight up to eight times more efficiently. Therefore, more robust and efficient photosynthesis will bring climate-proof, high-yielding food crops within reach. According to Collier et al. (2008), it may be possible to overcome problems in continuity of supply by changing to varieties with altered temperature requirements; however, further research will be required to identify or breed such adapted varieties. Thus, several projects, such as the EU projects TOMGEM (www.tomgem.eu) and/or TOMRES (www.tomres.eu), take place nowadays, in order to select superior tomato genotypes with improved adaptability of fruit production to suboptimal environmental conditions, or to combine novel genotypes with management strategies, having as a goal the reduction of fertilizer application amount and water input, while granting environmental sustainability and economic viability.

### 24.3.7 Ensuring Continuous Market Supply Under Climate Change

The challenge to supply year-round high-quality horticultural products can be afforded either by growing in high-tech greenhouses or by producing in different locations, whose harvesting periods are complementary. For instance, in the south of Spain, the absence of greenhouse production during the summer months in coastal areas is being substituted by the vegetable produce from screenhouses in the highlands, enabling the year-round market supply (Montero et al. 2009). Similarly, strawberry plants can be propagated under favourable conditions for floral induction in northern areas and then transplanted in southern areas to stimulate floral organ formation and development (Neri et al. 2012); growers are facing climate change with innovations in cultivated varieties and cultural techniques and by the integration of the different production areas, with their specific optimum yield seasons, to continuously fulfil the demands of the market.

### 24.3.8 Other Adaptation Possibilities

Other important factors are playing a central role in facing sustainable agriculture under climate change, e.g. farmer incentives (Tilman et al. 2002). More publicity and more private investment in resources and technology are desirable internationally and also low-income nations make agriculture/horticultural systems more sustainable. The global research expenditures are less than 2% of agricultural GDP worldwide, 5.5% of agricultural GDP in developed countries, and 1% less in developing countries, and the increased food demand will occur during the next 50 years (Pardey and Beintema 2002; Tilman et al. 2002). Foley et al. (2011) stated that to achieve global food security and environmental sustainability, agricultural systems should be transformed to address the challenges of food production and environmental protection. According to Howden et al. (2007), multidisciplinary complications need multidisciplinary solutions, i.e. focusing more on integrated instead of disciplinary science and strengthening the interaction with decision-makers. Gruda et al. (2019) suggested that year-round fresh vegetables, produced in a sustainable way under covered areas, are a central cornerstone to address the future challenges of climate change.

## 24.4 Constraints in Adaptive Strategies in Protected Cultivation Under Climate Change (CC) in Dry Region

Climate change (CC) and agriculture are dependent on each other. On the one hand CC is affected by agricultural activity, and the effects rising from climate change also affect substantially on agriculture in terms of yield and crop losses in agriculture. A striking feature of greenhouse production is the large amount of energy consumption for heating, especially in temperate areas and during the cold season, but in hotter areas and tropical regions, it is essential to minimise temperature to obtain efficient yields. In cooler regions the main purpose of adopting greenhouses is mainly to increase the inner than the external temperature to avoid chilling and frost injury to the crop, but in hotter parts the purpose was vice versa to the cool areas. In tropical regions high temperatures encourage huge crop losses by promoting high transpiration and other nutritional losses. Consequently, high greenhouse gas (GHG) emissions are produced (Gruda et al. 2019). Anticipated climatic changes encourage the expansion of protected agriculture, i.e. greenhouses and screenhouses, within which external climatic effects are restrained. Climate change has already begun and its impacts on rural areas will be particularly affected as it impacts on natural resources, agriculture, overall biodiversity, and ecosystems like forests and coastal zones, as well as human health. While the trend of temperature increases gradually, key climate variables like precipitation are hard to project. This means that decision-making for climate change adaptation is fraught with uncertainty.

### 24.4.1 Climate Change Impacts

The climatic changes defined in the above will cause several harmful consequences both for resources and number of sectors such as water abundance, agriculture, and coastal zones. Climatic change will influence the magnitude and frequency of natural disasters. A slight change of temperature can have major effects on systems where human's livelihoods depend, which includes crop productivity and water availability, land loss by rising sea level, and the spread of disease. Decreased snow cover will affect snow-fed and glacial systems such as the Ganges and Brahmaputra. Erratic monsoons will affect rainfed agriculture, peninsular rivers, and water and power supply. Wheat production will drop by 4–5 million tonnes, even with a rise in temperature of only 1°C. Rising sea levels will cause displacement in densely populated coastlines in the world, also threatening freshwater sources and mangrove ecosystems. Floods will increase in frequency and intensity. This will heighten the vulnerability of people in the coastal, arid, and semi-arid zones. Over 50% of forests are likely to experience shift in forest types, adversely impacting associated biodiversity, regional climate dynamics, and livelihoods based on forest products.

#### 24.4.1.1 Impacts of Climate Change on Crop Production in Protected Environments

Climate scenarios like the four representative concentration pathways (RCPs), RCP2.6, RCP4.5, RCP6.0, and RCP 8.5, were designed by the scientific community for the IPCC's Assessment Reports (IPCC, 2013). The future impacts of these climate change scenarios on production of greenhouse vegetables are difficult to predict because of the large differences, including drastic changes, as well as more moderate scenarios. However, by studying regional and global climate simulations, we can attempt to deduce some possible impacts on greenhouse vegetable production and the resulting shift of quality which could potentially become a reality even in the near future.

#### 24.4.1.2 The Impacts of Increasing Atmospheric $CO_2$

By mid-century, carbon dioxide ($CO_2$) levels are anticipated to rise to between 442 ppm (RCP2.6) and 540 ppm (RCP8.5) in the atmosphere (IPCC 2013). Increased yields are common when producers supplement $CO_2$ levels in their veggies. More atmospheric $CO_2$ may lower $CO_2$ fertilisation input costs, but this practice will become obsolete in the near future as plants can benefit from even higher levels than those predicted; the most pessimistic scenario, the RCP8.5, forecasts atmospheric $CO_2$ concentrations of 935 ppm in 2100 (IPCC 2013). When compared to a non-enriched greenhouse, greenhouse yields of eggplant, cucumber, and pepper were high (Akilli et al. 2000). However, in vented greenhouses, the time of year when plants benefit the most is when $CO_2$ corresponds with the time of year when ventilation requirements are highest, rendering $CO_2$ enrichment inefficient and costly due to losses to the outside (Bisbis et al. 2018a, b). With the forecasted rise in heat waves and the resulting increase in the frequency of required ventilation, it is expected to become more pronounced (Bisbis et al. 2018a, b). As a result, rising $CO_2$ levels in the atmosphere may benefit agricultural output, especially during the summer and depending on the current climate scenario. The influence of $CO_2$ on vegetable quality was examined by Dong et al. (2018a). In the edible part of vegetables, increased $CO_2$ concentrations increased the concentrations of fructose, glucose, total soluble sugar, total antioxidant capacity, total phenols, total flavonoids, ascorbic acid, and calcium, but decreased the concentrations of protein, nitrate, magnesium, iron, and zinc, according to the authors of a meta-analysis.

Increased nitrogen uptake by the crop will result from expected increases in atmospheric $CO_2$ concentrations, necessitating more fertilizer applications (Dong et al. 2018b, c). Changes in climate may alter nitrogen losses by leaching or gaseous losses, with the direction of change varying depending on the unique climate change at a place. Changes in fertilizer demand may result (Bindi and Howden 2004). $CO_2$ from the atmosphere may have a stronger influence on screenhouses. As a result, increased $CO_2$ concentrations in the atmosphere may benefit the crop directly. However, due to the porous structure of the cover and the high mass exchange with the outside environment, $CO_2$ enrichment may be ineffective (Tanny et al. 2003).

#### 24.4.1.3 The Impacts of Changing Precipitation Patterns

Precipitation patterns in Northern Europe change with an increase in rainfall in the autumn, winter, and spring and decrease in the summer, when huge amounts of water are required (Jacob et al. 2014). Furthermore, because of climate change impacts, the spatial distribution of rainfall in some areas is shifting, resulting in water shortages in some areas. Because irrigated horticulture consumes a lot of water, there will be increased rivalry among water users in the future (Bisbis et al. 2018a, b). Plants will undergo drought stress if growers fail to maintain proper irrigation due to water scarcity, which could lead to crop loss (Gruda et al. 2009). Saadi et al. (2015) found that between 2000 and 2050, yearly precipitation will decrease by 39.1–55.1 mm and air temperature will be rise by 1.57 0.27 °C (from 0.84 to 2.31 °C), according to a study on the influence of CC on agricultural production of winter wheat and tomato in the Mediterranean region. However, the growing season length is probably shortening, reduced by crop evapotranspiration by 6% and 5% for wheat and tomato, respectively, and net irrigation requirements under optimal water supply by 11% and 5% for wheat and tomato, respectively. Because greenhouse plants are in a protected environment, the impact of external weather conditions is predicted to be reduced. Winters will very certainly be accompanied with greater sky cover if precipitation increases in the winter, unless the majority of it falls in brief bursts of heavy rain. Aside from the short days, the low amount of solar radiation during the winter season is already a major limiting factor for productivity. Plant performance and product quality are both harmed by low light intensity (Gruda 2005; Gruda and Tanny 2015). Solar radiation is a limiting factor in northern latitudes, such as the Netherlands, where 1% of light loss is projected to result in a 0.5–1% yield reduction in vegetables and ornamentals (Marcelis et al. 2006). CC's effects on productivity in the Chinese solar greenhouse system were investigated in a study conducted in China (Ge and Zhang 2006). The findings revealed that in the winter, severe low air temperatures, fog, and fully cloudy days all rose. In the north and south of the Weihe River, however, the trend of climate variations was distinct. As a result, the recommendations were to enhance vegetable and fruit greenhouse production in Dali County while reducing greenhouse output in the Weihe River valley.

#### 24.4.1.4 The Impacts of High Summer Temperatures

In comparison to 1986–2005, climate change models forecast a rise in global mean temperature of 1 °C (RCP2.6) to 2 °C (RCP8.5) until the middle of the century (IPCC 2013). This means that summers in Western Europe will be marked by longer and extreme frequent heat waves, as well as temperature extremes never seen before (IPCC 2013). According to a review by Cramer et al. (2018), the Mediterranean has already experienced a temperature rise of 0.4 °C above the global average, and increased temperature may reduce summer precipitation by up to 30% and increase irrigation demand by up to 18% in some regions until the end of the century, according to future projections. Even in sheltered cops, high temperatures and unpredictable weather events can result in uneven yields and waste. The explanation could be physiological in nature, such as uneven ripening, soft fruit, poor/late set, and delayed ripening of truss types in tomatoes or difficulty in anticipating crop cultivation sequences in other crops (Collier et al. 2008). Furthermore, heat stress during flowering can delay fruit set and later cause BER and sunburns on fruits (Gruda 2005; Abdelmageed and Gruda 2009), lowering yield and increasing waste products (Gruda 2005; Abdelmageed and Gruda 2009) (Bisbis et al. 2018a). Crops that require a steady supply of nutrients, such as green vegetables, are particularly sensitive to harsh weather. For reliable scheduling, these crops usually rely on a combination of successional plantings and the right genotypes. Increased temperature changes may cause harvest dates to be pushed forward (Collier et al., 2008).

#### 24.4.1.5 The Impacts of Elevated Temperatures on Pests and Diseases

Not only will climate change effect vegetable harvests, but it will also disrupt insect pest life cycles and reproduction rates. Winter death rates of insects would decrease as global temperatures rise, allowing for earlier and stronger infestations, with more generations per year, for example, aphids, and the introduction of new species, such as *Tuta absoluta* (Hulle et al. 2010; Van Damme et al. 2014; Bisbis et al. 2018a). Increasing atmospheric $CO_2$ can also affect plant-insect interactions by changing the host plant's food quality, which can result in lower insect health or increased infestation intensity depending on the species involved (Dader et al. 2016). Changes in wind speed and direction are anticipated to have a major influence on pest and disease prevalence and transmission, despite the fact that current climate models do not include wind prediction (Collier et al. 2008). Teitel et al. (2005) found that the number of whiteflies was higher near the roof opening through which wind entered the greenhouse in a naturally ventilated greenhouse in which pepper was grown. This implies that climate change-induced changes in wind speed and direction may affect insect entry into greenhouses. Food safety is a crucial part of human nutrition, in addition to ensuring food supply. *Alternaria* mould may appear more frequently in cool locations, such as Poland, and less frequently in warm regions, such as Spain, by means of global warming, resulting in changes in mycotoxin content in fruits (Van de Perre et al. 2015) demonstrated in tomato. Winters are growing milder on account of the rising temperatures (Bisbis et al. 2018a). Warm winter temperatures typically result in increased rates of crop transpiration and reduce the greenhouse's vapour pressure deficit. Increased winter precipitation together with hotter days would exacerbate the problem. This winter pattern recognises the need for better greenhouse humidity control in the future to avoid phytosanitary issues including mildew, *Botrytis*, and grey mould, as well as other product quality issues (Gruda and Tanny 2014; Bisbis et al. 2018a, b).

## 24.5 Conclusions and Future Prospects

This chapter presents the effects of climatic change on protected cultivation, the different facets of climate change, and how this affects the greenhouse horticulture in the future as well as innovation-based adaptation strategies to overcome or mitigate those impacts. Changes in climate can interact with other greenhouse parameters and affect plant growth, yield, and quality of produce. It is our belief that research and development of controlled environment agriculture systems should move forward into two main directions. The first is hi-tech greenhouses, equipped with state-of-the-art active climate control and management systems. Such structures are more feasible for long-term production of a specific crop which is under stable and high consumer demand. This is because investment in such structures and the associated control devices is high and hence requires high and stable economical return. The second direction is low-tech greenhouses, based on passive climate control, including naturally ventilated greenhouses and screenhouses. These structures are low cost and will be affordable for regions where agricultural production is less stable economically and in developing countries where farmers cannot afford high investments. Obviously protected cultivation systems of intermediate level, e.g. greenhouses equipped with a wet pad cooling system, are also feasible, depending on specific crop and regional climate. Low-cost structures like naturally ventilated greenhouses and screenhouses will become more popular as an alternative to open-field cultivation. This is because such structures will moderately restrain the effects of climate change while keeping the production highly sustainable and environmentally friendly in terms of water and energy consumption. The adaptations that we presented in this require a new redesigned, multidisciplinary research approach starting with genetics and crop physiology, through greenhouse engineering, plant phenotyping and modelling, and modern farming management and optimisation while ensuring social acceptance.

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# Organic Farming: Prospects and Challenges in Drylands

# 25

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and Pintoo Bandopadhyay

**Abstract**

Every technology or interference in the natural ecosystem has its own side effect; from the last half a century we are using pesticides and herbicides indiscriminately to raise crop production, but now their ill effect is visible to us. Now that we achieve the self-sufficiency in food grain production, our next motto is to serve healthy food to people. We are looking for alternative nature-based chemical-free farming and that is organic farming. It also helps to get the premium price by exporting the chemical-free agriculture commodity to the developed countries; day-by-day demands for a healthy and residue-free food increase all over the world as well as the country itself. The population in dryland areas is currently growing at a rate of 2.3% per year which is unable to earn year-round livelihood in their own village. Since organic agriculture is labor-intensive and relies on local input, it provides food security and ample opportunity for local employment and proper utilization of this precious human resource. The dryland areas are a key region for small grain, forage, pulse, and oilseed production. Expansion of area under organic cultivation with realisations of its outcomes, the consequent floral biodiversity is expected to contribute to the ecosystem services also in the agricultural landscapes of dry tract areas in India.

**Keywords**

Conventional farming · Future prospects · India · Organic farming · Drylands

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## 25.1 Introduction

Following independence, an increase in population in India has placed enormous pressure on agricultural land due to huge demands for agricultural food grain production that leads to an increase in the use of synthetic fertilizers and pesticides to boost agricultural production. So in 1965, the government with the help of the Indian father of the green revolution, M.S. Swaminathan, launched high-yielding variety (HYV) seeds in Indian agriculture with better and more efficient irrigation facilities and the correct use of fertilizers to boost the production. The main aim of the Green Revolution was to make India self-sufficient in grain production. The Green Revolution in India refers to a certain interval of time when people started using HYV seeds, pesticides, tractors, and other types of equipment in agriculture. Foods grown with chemical fertilizers caused various deteriorating health hazards in animals as well as human beings. Moreover, there is a growing demand for organic foods driven primarily by the consumer's perceptions of the quality and safety of these foods and the positive environmental impact of organic agriculture practices. It has been demonstrated that organically produced foods have lower levels of pesticides and veterinary drug residues and in many cases lower nitrate contents. As synthetically produced pesticides and chemical fertilizers are utilized, consumption of conventionally grown foods is discouraged for the continuous growth of food hazards and several other environmental issues. The popularity of organic food is growing dramatically as consumer seeks organic foods that are thought to be healthier and safer. With the present day awareness level of the consumers, food quality and safety is gradually on the decline. For these reasons, consumers are focused on safer and better quality food items that are produced more ecologically without the use of chemical inputs. Organic agriculture, a holistic system that focuses on soil health improvement, use of local inputs, and relatively high-intensity use of local labor, is an admirable fit for drylands in many ways. And, in fact, India's National Project on Organic Farming (NPOF), launched in 2004, has given top priority to the drylands (NPOF 2005). Organic agricultural products protect the environment by enhancing agro-ecosystem health and improving soil biological activity that facilities the development of a socially, ecologically, and economically sustainable food production system. Organic farming relies on crop rotation, crop residues, animal manures, legumes, green manures, off-farming organic wastes, agricultural cultivation, mineral-bearing rocks, and aspect of biological pest control to maintain soil productivity and tilth to supply plant nutrients and also to control insects, weeds, and other pests (Lampkin 1990). Organic source of the nutrient also helps to combat the problem of several multi-nutrient deficiencies, and in dryland areas, low organic content adversely affects the production of food crops on farmland. Organic farming keeps soil healthy and maintains environment integrity, thereby promoting the health of consumers. Moreover, the organic produce market is now the fastest-growing market all over the world including in India. Organic and ecological farming has been observed to be feasible in the long run in terms of soil fertility, stability of crop yields, and economy. The population in dryland areas is currently growing at a rate of 2.3% per year which is unable to earn a year-round livelihood in their own village. Since organic agriculture is labor-intensive and relies on local input, it provides food security and ample opportunity for local employment and proper utilization of the available resources. In terms of input supply, the arid areas are very rich in local resources suitable for supporting organic agriculture like neem (*Azadirachta indica*), karanja (*Pongamia pinnata*), and *Calotropis* spp. which are abundantly available in drylands and can be used as best sources of biopesticides (Rao Rajeshwar 1999). Similarly, minerals like rock phosphate, gypsum, and lime are available naturally in large quantities in Rajasthan. Since organic farming is labor-intensive and relies on local inputs, it can provide both improved local food security and ample opportunities for local employment and proper utilization of this precious human resource (Gupta and Sharma 1996). Organic agriculture combines tradition, innovation, and science to benefit the shared environment and promote fair relationships and good quality of life for all involved. Despite initial years of organic agriculture have compromised yield levels, it paves the way for more environmentally friendly and nutritous food and unerpins its value to the agroecosystem and social profit. However, due to the yield gap between organic and conventional agriculture, the differences in the cost efficiency are profound, so organic agriculture continues to be a minor option for conventional cultivation. Ardent promoters of organic farming consider that it can meet both these demands and become the means for the complete development of rural areas. After almost a century of development, organic agriculture is now being embraced by the mainstream and shows great promise commercially, socially, and environmentally. In today’s terminology, it is a method of a farming system that primarily aims at cultivating the land and raising crops in such a way as to keep the soil alive and in good health by the use of organic wastes (crop, animal and farm wastes, aquatic wastes) and other biological materials along with beneficial microbes (biofertilizers) to release nutrients to crops for increased sustainable production in an eco-friendly and pollution-free environment.

## 25.2 Benefits of Organic Farming

Organic agricultural practices are based on a harmonious relationship with nature aiming at the non-destruction of the environment. The major problem in India is the poor productivity of soils because of the low-level content of organic matter. So, the organic farming system is looked upon as one of the means to remedy these maladies to sustain the food demand for an ever-increasing population.

### 25.2.1 Improvement in Soil Quality

Soil quality is the foundation on which organic farming is based. Efforts are directed to build and maintain soil fertility through farming practices. Natural plant nutrients from green manures, farmyard manures, composts, and plant residues build organic content in the soil. It is reported that soil under organic farming conditions had lower bulk density, higher water-holding capacity, higher microbial biomass carbon and nitrogen, and higher soil respiration activities compared to conventional farms (Sharma 2003). This indicates that sufficiently higher amounts of nutrients are made available to the crops due to enhanced microbial activity under organic farming.

### 25.2.2 Nutritional Benefits and Health Safety

Magnusson et al. (2001) and Brandt and MØlgaord (2001) mentioned that the growing demand for organically farmed fresh products has created an interest in both consumers and producers regarding the nutritional value of organically and conventionally grown foods. According to a study conducted by AFSSA (2003), organically grown foods, especially leafy vegetables and tubers, have higher dry matter as compared to conventionally grown foods. Although organic cereals and their products contain lesser protein than conventional cereals, they have higher quality proteins with better amino acid scores. Lysine content in organic wheat has been reported to be 25–30% more than in conventional wheat (Woëse et al. 1997; Brandt et al. 2000). Organically grazed cows and sheep contain less fat and more lean meat as compared to their conventional counterparts (Hansson et al. 2000). In a study conducted by Nürnberg et al. (2002), organically fed cow's muscle contains fourfold more linolenic acid, which is a recommended cardio-protective ω-3 fatty acid, with an accompanying decrease in oleic acid and linoleic acid. Pastushenko et al. (2000) found that meat from an organically grazed cow contains high amounts of polyunsaturated fatty acids. Organic plants contain significantly more magnesium, iron, and phosphorus. They also contain more calcium, sodium, and potassium as major elements and manganese, iodine, chromium, molybdenum, selenium, boron, copper, vanadium, and zinc as trace elements (Rembialkowska 2007).

### 25.2.3 Socioeconomic Impact

Organic cultivation requires a higher level of labor, hence producing more income-generating jobs per farm (Halberg 2008). On the input side, factors that enhance the price of organic foods include the high cost of obtaining the organic certification, the high cost of manpower in the field, and the lack of subsidies on organics in India, unlike chemical inputs. But consumers are willing to pay a high price as there is increasing health awareness. Biofertilizers and pesticides can be produced locally, so yearly inputs invested by the farmers are also low (Lobley et al. 2005). As the labors working on organic farms are less likely to be exposed to agricultural chemicals, their occupational health is improved (Thompson and Kidwell 1998). Organic farming is now an expanding economic sector as a result of the profit incurred by organic produce, thereby leading to a growing inclination towards organic agriculture by the farmers.

## 25.3 Specific Benefits of Organic Farming for the Drylands of India

- Maintaining sustainability in the global economy: balancing organic principles with commercial imperatives
- Maintaining flexible organic standards and certification processes to address issues such as:
  1. Nature conservation and regeneration
  2. Equitable, affordable, and flexible access to certification services
  3. Responsible labor relations and land tenure arrangements and animal welfare
  4. New inputs such as “natural” biocides, soil amendments, and GMOs
  5. Incomplete or unscientific basis for including/excluding materials from organic standards.
- Pursuing international harmonization of standards and certification
- Developing locally applicable agronomic solutions to production constraints, such as weeds, animal health, and soil fertility
- Expanding research activities in many disciplines (particularly beyond Europe and North America) and foster the integration of knowledge
- Preserving food quality while trying to increase productivity
- Educating and training at all levels to build capacity, infrastructure, and networks
- Inadequacies in regulatory and marketing structures (e.g., labeling)
- Excessive consumer prices and inconsistent quality and availability
- Establishing and maintaining credibility and professionalism

## 25.4 Challenges for Organic Agriculture

Organic farming with its central focus on maintaining and improving soil health by avoiding the pollutants and suitable use of local inputs and labor can advance the economic and ecological health of the arid regions. Semi-arid and arid dryland soils typically are poor in water-holding capacity and low in organic matter (Sharma 2000). The addition of organic matter will not only improve the physical condition of dryland soils but also greatly improve their ability to supply balanced nutrients suitable for plant growth. In drylands, there is overexploitation of natural resources (Reddy 2010) mainly because of inappropriate production-enhancing technologies. For example, the use of tractors increases wind erosion and damages the natural regeneration of trees and grasses. In many locations where intensive-input agriculture systems are followed, soil fertility is decreasing and certain severe pests are becoming resistant to synthetic pesticides (Butterworth et al. 2003). These are all indicators of improper land use, leading to desertification; adoption of organic farming practices suitable for drylands can help to ameliorate these conditions. Soil and climate conditions in India’s drylands make them particularly well suited to organic agriculture. These marginal lands, with their marginal soils, tend not to respond well to intensive farming practices. They are actually better suited to low-input farming systems that make ample use of biodiversity (Sharma 1998). In turn, organic farming, with its central focus on maintaining and improving soil health, its avoidance of pollutants, and its reliance on local inputs and labor, can materially advance the economic and ecological health both of the drylands and the people who live there. In some areas depth of soil is another limiting factor for agricultural production. The addition of organic matter, a cornerstone of organic farming practices, will not only improve the physical condition of these dryland soils but also greatly improve their ability to supply balanced plant nutrients. Furthermore, as stated in the introduction, dryland desertification is increasing at an alarming rate due to the overexploitation of natural resources. For example, the use of tractors increases wind erosion and damages the natural regeneration of trees and grasses. Over-use or improper use of canal irrigation can cause waterlogging and salinity (not to mention malaria epidemics). Excessive groundwater pumping has decreased the groundwater table drastically in tube well-irrigated areas. In many locations where intensive-input agriculture systems are followed, soil fertility is decreasing and certain severe crop pests are becoming resistant to synthetic pesticides. These all are indicators of improper land use leading to desertification; adoption of organic farming practices suitable for drylands can help to ameliorate these conditions. Another serious problem in drylands is the lack of sufficient food security or economic opportunity for the many people who live there. The population in these drylands areas is currently growing at a rate of 2.8% per year. Yet, under current practices, many dryland farmers are unable to earn a year-round livelihood in their own villages. The consequent migration of villagers to cities and nearby states for livelihood during drought further imbalances the economic development of these drylands. Since organic farming is labor-intensive and relies on local inputs, it can provide both improved local food security and ample opportunities for local employment and proper utilization of this precious human resource (Gupta and Sharma 1996). To be sure, many farmers resist implementing organic systems because they fear a drop in productivity and thus income, during the years while synthetic fertilizer/pesticide use is discontinued and the soil is gradually built up by organic means. However, the longest transition periods occur where pesticide use has previously been greatest. And because of the lack of a reliable water supply and average fertilizer use in the semi-arid, rainfed drylands, 67% of India's agricultural area is already very low (36.4 kg/ha) compared to that of the national average of 76.8 kg/ha. In the actual desert areas, fertilizer use is negligible (FAI 1998). Pesticide use is also very low. Furthermore, large parts of the drylands are still categorized as "virgin," meaning no synthetic inputs have been used there to date. This makes a quick shift to organic agriculture, with no drop in productivity, much easier. Due to climatic variability, farming systems in drylands traditionally mix crops, trees, animals, grasses, etc. Such diversified systems have been found efficient in nutrient recycling and restoration of soil fertility, the basic aims of organic farming; they minimize pest incidence as well. Furthermore, India's traditional farmers possess a rich body of wisdom, based on long observation and practice, concerning soil fertility management and pest control; this can be drawn on to further strengthen organic systems (Sharma and Goyal 2000). These two factors will also aid in the quick development of more efficient and more productive organic farming systems in these areas.

## 25.5 Strategies for Promoting Organic Farming in Drylands

As shown above, there is immense potential for the adoption of organic farming in India's drylands (Sharma 2001). Socioeconomic and ecological reasons also favor it (Arora and Mohan 1986): many aspects of drylands that would pose constraints for the intensive agriculture system of the Green Revolution can be converted into opportunities for organic farming. The following specific steps would go a long way towards promoting this development.

### 25.5.1 Popularize Organic Farming Without the Compulsion of Certification

In drylands, farmers are very poor and are largely unable to afford the cost of certification programs. Promoting certification as a universal requirement of organic farming has thus had a negative impact on its adoption by smallholders in these areas. A more appropriate approach for drylands, at least during a certain initial period until the industry is established, would be to promote non-certified organic farming with a goal of providing local employment and improving local/regional food security rather than developing export crops.

### 25.5.2 Promote Ley Farming

In India's drylands, rotation of grasses and food grains is known as ley farming. This system is traditional; research by the Central Arid Zone Research Institute (CAZRI) has validated it as one of the best options for fertility restoration in these regions (Muthana et al. 1985).

### 25.5.3 Integrate Efforts of Supporting Agencies

Several government agencies and NGOs are working individually to promote organic farming. This individual approach, however, may result either in lack of adequate funding or lack of adequate knowledge of organic farming and/or marketing techniques. For example, rural ministries have a scheme of "margin money" in which they subsidize 25–30% of loans made to establish vermicompost units, but they are unable to ensure a steady market for the produce of such units. Similarly, state agriculture departments and the institutes that make up the Indian Council of Agricultural Research (ICAR) have a wealth of information on organic farming but are unable to provide financial support for initiating such programs. Thus, there is a need for all related agencies to create integrated programs, linking the storehouses of technologies with financial institutions, in order to effectively promote organic farming. Since funding agencies always have the financial upper hand, they must take the lead to ensure sufficient technology backup and marketing of these products. This could be effected through a coordinating committee with representatives from all concerned organizations.

### 25.5.4 Encourage Decentralized Input Supply

Local, decentralized production of all inputs for organic farming should be encouraged not only so that local resources can be utilized but also so that village-level employment can be generated. Locally produced inputs are also much less likely to be adulterated. All of this organic input production should be legally categorized as cottage industry. Subsidies or micro-financing to help set up small-scale input production units that meet local requirements could be provided to village cooperatives and self-help groups (i.e., informal groups of people with a joint livelihood system and a common bank account). Banning inter-state transportation of organic inputs could be another effective method for keeping such production local.

### 25.5.5 Adopt Improved Methods of Composting

In general, farmers understand the importance of adding organic matter to drylands soils, but the majority apply undecomposed animal and crop wastes. This not only reduces the availability of nutrients to plants but also invites several pests. It would be better to apply these materials after composting them (Durgude et al. 1996) with any of several suitable methods. Because these composting methods would help reduce disease and improve local sanitary conditions, they could be popularized and financially supported under India's existing "Clean village scheme." This scheme, sponsored by the government's Ministry of Rural Development and executed by state governments and volunteer organizations, focuses on the safe disposal and use of human and animal wastes as a means of improving hygiene and health at the village level.

### 25.5.6 Increase Public Awareness and Build Capacity

Conferences, seminars, and farmers' fairs may be organized to raise awareness and encourage the adoption of organic farming. Programs demonstrating how to establish organic systems and training in how to produce and manage organic inputs may be started at the village level. Under the NPOF, sufficient provision has been made to train farmers for organic production and internal control and to develop both model organic farms and a nationwide network of organic service providers (to provide guidance, establish farmers' groups, and arrange organic inputs). However, most of these programs focus on irrigated areas because of ensured success and export possibilities. A rational allocation policy for drylands is needed.

### 25.5.7 Subsidize Organic Inputs and Produce

Subsidies may be provided for organic inputs and produce while the industry is still getting established. In India, subsidies are mainly provided by the national government and channeled through state agriculture departments; the technique is well-tested, having already been used for the synthetic fertilizer and pesticide industry. Indeed, subsidies have been provided for setting up biofertilizer and vermicomposting units under NPOF and for setting up export schemes under NPOP. Additional subsidies could be provided for:

- Setting up organic input production units for composting, biopesticides, etc.
- Compensating organic farmers during the period of conversion to organic techniques, to compensate for yield reductions if any
- Establishing village-level grading and packaging units for organic produce
- Developing local and regional marketing infrastructure for organic produce in dryland areas, where regional/local food security is more important than crops for export

### 25.5.8 Promote High-Value Crops

The dryland climate favors the quality production of several spices and medicinal plants that are already in great demand both nationally and internationally. Furthermore, demand for organic versions of these high-value products is increasing. Thus, once the local market is well established and the potential for growing crops for export has increased, they may be promoted to dryland farmers as excellent plants to include in the overall design of their organic system.

### 25.5.9 Develop Organic Farming Clusters of Villages

Since the drylands are already an area of focus for governmental development programs based on a watershed approach, clusters of villages previously established for such programs (Khan 2002) may be converted into organic clusters of villages by providing technical support. This will be cost-effective and make the eventual certification process of organic produce easier for these villages once the local organic produce market has been well established.

### 25.5.10 Develop Certification Programs and Marketing Chains

Ultimately, once the dryland organic agriculture industry is strong, cost-effective facilities for the sale of certified organic produce in regional and global markets may be created. The cost of certification should be met by the exporters. Organic farming can be defined as an agricultural process that uses biological fertilizers and pest control acquired from animal or plant waste. Organic farming was actually initiated as an answer to the environmental sufferings caused by the use of chemical pesticides and synthetic fertilizers. In other words, organic farming is a new system of farming or agriculture that repairs, maintains, and improves the ecological balance.

## 25.6 Organic Farming for the Drylands of India: Ecological Sustainability

Soil and climate conditions in India's drylands make them particularly well suited to organic agriculture. These marginal lands, with their marginal soils, tend not to respond well to intensive farming practices. They are actually better suited to low-input farming systems that make ample use of biodiversity (Sharma 1998). In turn, organic farming, with its central focus on maintaining and improving soil health, its avoidance of pollutants, and its reliance on local inputs and labor, can materially advance the economic and ecological health both of the drylands and of the people who live there. To begin with, semi-arid and arid dryland soils typically are poor in a water-holding capacity as well as organic matter (Sharma 2000). In some areas depth of soil is another limiting factor for agricultural production. The addition of organic matter, a cornerstone of organic farming practices, will not only improve the physical condition of these dryland soils but also greatly improve their ability to supply balanced plant nutrients. Furthermore, as stated in the introduction, dryland desertification is increasing at an alarming rate due to the overexploitation of natural resources. This is mainly because of production-enhancing technologies that are inappropriate in drylands (Dhir 1997). Over-use or improper use of canal irrigation can cause waterlogging and salinity (not to mention malaria epidemics). Excessive groundwater pumping has decreased the groundwater table drastically in tube well-irrigated areas. In many locations where intensive-input agriculture systems are followed, soil fertility is decreasing and certain severe crop pests are becoming resistant to synthetic pesticides. These all are indicators of improper land use leading to desertification; adoption of organic farming practices suitable for drylands can help to ameliorate these conditions. Another serious problem in drylands is the lack of sufficient food security or economic opportunity for the many people who live there. Since organic farming is labor-intensive and relies on local inputs, it can provide both improved local food security and ample opportunities for local employment and proper utilization of this precious human resource (Gupta and Sharma 1996). To be sure, many farmers resist implementing organic systems because they fear a drop in productivity and thus income, during the years while synthetic fertilizer/pesticide use is discontinued and the soil is gradually built up by organic means. However, the longest transition periods occur where pesticide use has previously been the greatest. And because of the lack of a reliable water supply and average fertilizer use in the semi-arid, rainfed drylands, 67% of India's agricultural area is already very low (36.4 kg/ha) compared to that of the national average of 76.8 kg/ha. In the actual desert areas, fertilizer use is negligible (FAI 1998). Such diversified systems have been found efficient in nutrient recycling and restoration of soil fertility. Furthermore, India's traditional farmers have rich legacies of indigenous technical knowledge and this can be drawn on to further strengthen organic systems (Sharma and Goyal 2000). These two factors will also aid in the quick development of more efficient and more productive organic farming systems in these areas.

## 25.7 Main Principles of Organic Farming

The main principles of organic farming (Chandrashekar 2010) are as follows:

- To work as much as possible within a closed system and draw upon local resources
- To maintain long-term fertility of soils
- To avoid all forms of pollution that may result from agricultural techniques
- To produce foodstuffs of high nutritional quality and in sufficient quantity
- To reduce the use of fossil energy in agricultural practice to a minimum
- To give livestock conditions of life that conform to their physiological needs
- To make it possible for agricultural producers to earn a living through their work and develop their potential as a human being

## 25.8 Future Prospectus of Organic Farming

India is an agriculture-based country with 67% of its population and 55% of manpower depending on farming and related activities. Agriculture fulfills the basic needs of India's fastest-growing population accounting for 30% of total income. Organic farming has been found to be an indigenous practice in India that is practiced in countless rural farming communities over the millennium. The arrival of modern techniques and increased burden of population led to a propensity towards conventional farming that involves the use of synthetic fertilizer, chemical pesticides, application of genetic modification techniques, etc. Even in developing countries like India, the demand for organically grown produce is more as people are more aware now of the safety and quality of food, and the organic process has a massive influence on soil health, which is devoid of chemical pesticides. Organic cultivation has an immense prospect of income generation too (Bhardwaj and Dhiman 2019). The soil in India is bestowed with various types of naturally available organic nutrient resources that aid in organic farming (Adolph and Butterworth 2002; Reddy 2010; Deshmukh and Babar 2015). India is a country with a concrete traditional farming system, ingenious farmers, extensive drylands, and nominal use of chemical fertilizers and pesticides. Moreover, adequate rainfall in northeast hilly regions of the country where few negligible chemicals are employed for a long period of time comes to fruition as naturally organic lands (Gour 2016). The earth's land surface is covered by drylands forming about 41% which is inhabited by two billion people (about one-third of the world's population). Drylands are areas with low soil moisture and high evapotranspiration, which results in water deficit prevailing throughout the year. The drylands are not equally distributed between the rich and the poor nations. About 72% of the global dryland is in developing nations and the remaining 28% falls in industrialized nations. In a country like India, 44% of the total food production is supported by drylands and is thereby playing a critical role in the nation's food security. With the increasing population, food production has to be increased. A real need for a second Green Revolution has been envisioned, which can be achieved by improving dryland agriculture. Geographically dryland agriculture area in India includes the northwestern desert regions of Rajasthan; the plateau region of central India; the alluvial plains of Ganga Yamuna river basin; the central highlands of Gujarat, Maharashtra, and Madhya Pradesh; the rain shadow regions of Deccan in Maharashtra; the Deccan Plateau of Andhra Pradesh; and the Tamil Nadu highlands (Rao and Ryan 2004; Singh et al. 2004).

## 25.9 Organic Agriculture and Sustainable Development

The concept of sustainable agriculture integrates three main goals: environmental health, economic profitability, and social and economic equity. The concept of sustainability rests on the principle that we must meet the needs of the present without compromising the ability of future generations to meet their own needs. The very basic approach to organic farming for a sustainable environment includes the following:

1. Improvement and maintenance of the natural landscape and agro-ecosystem
2. Avoidance of overexploitation and pollution of natural resources
3. Minimization of the consumption of non-renewable energy resources
4. Exploitation synergies that exist in a natural ecosystem
5. Maintenance and improvement of soil health by stimulating activity or soil organic manures and avoiding harming them with pesticides
6. Optimum economic returns, with a safe, secure, and healthy working environment
7. Acknowledgment of the virtues of indigenous know-how and traditional farming system

Organic farming fetches premium price in the market and are therefore farming is more profitable to the growers and stakeholders. The increase in the cost of production by the use of pesticides and fertilizers in conventional farming and its negative impact on farmer's health affect the economic balance in a community.

Continuous degradation of soil fertility by chemical fertilizers leads to production loss and hence increases the cost of production which makes the farming economically unsustainable. Implementation of a strategy encompassing food security, generation of rural employment, poverty alleviation, conservation of the natural resource, adoption of an export-oriented production system, sound infrastructure, and active participation of government and private-public sector will be helpful to revamp economic sustainability in agriculture (Soumya 2015).

## 25.10 Social Sustainability

It is defined as a process or framework that promotes the well-being of members of an organization while supporting the ability of future generations to maintain a healthy community. Social sustainability can be improved by enabling rural poor to get benefit from agricultural development, giving respect to indigenous knowledge and practices along with modern technologies, promoting gender equality in labor, and full participation of vibrant rural communities to enhance their confidence and mental health, thus decreasing suicidal rates among the farmers. Organic farming appears to generate 30% more employment in rural areas and labor achieves higher returns per unit of labor input (Pandey and Singh 2012).

## 25.11 Importance of Dryland Farming

### 25.11.1 Characteristics of Dryland Agriculture in India

Rainfall: The most important discouraging characteristic in the dryland for agriculture is low rainfall, within a range of 375 mm to 1125 mm, which are unevenly distributed, highly erratic, and uncertain. The crop production in drylands is mainly dependent on the frequency and intensity of rainfall, making it less productive.

Soil: The major causes for land degradation include the chemical degradation of soil, loss of soil structure and texture, and loss of natural vegetation leading to soil erosion. Sequestration of carbon also turns out to be a major problem, which further degrades the soil, making it a less productive occurrence of drought: the extensive climatic hazards are seen in drylands as the soils are weak and can be subjected to environmental stress to a higher level, leading to further land degradation. Drought is a common scenario in drylands as water availability is less, further leading to low productivity.

Extensive agriculture: The prevalence of monocropping extensively makes farmlands lack nutrients and results in a reduction of yield.

The crops grown in a particular region will be similar and are not much remunerative compared to the major crops like rice and wheat. When similar crops are grown, all mature at the same time and a large quantity of produce will reach the market leading to glut in the markets. This situation is severely exploited by the traders and the middlemen in the markets. The issue of marketing turns out to be a big problem in dryland agriculture.

Poor economy of farmers: Economic status and living of farmers is low in drylands, due to the less choice of the crops that are grown in these areas.

## 25.12 Problems of Dryland Farming

Soils are highly diverse in the drylands of India. In semi-arid regions, the alfisols and vertisols predominate, whereas in river basins inceptisols and entisols (alluvial soils) are seen and in desert regions, aridisols (Peterson et al. 2006). Crops grown in alfisols are subjected to severe drought stress, whereas those grown in vertisols have less severity to drought, due to its better water-holding capacity. Vertisols are poor in infiltration leading to salinity. Alluvial soils of arid regions have low soil fertility, but respond well to inputs and are highly productive under irrigated conditions. Wind erosion predominates in aridisols. Soil degradation has many related factors, with soil compaction and degraded levels of organic matter found to be the most important causes in South Asia as a whole. Soil erosion by water is found to be the major cause in mountainous areas and in undulating terrains in Central India. With the improvement of irrigation facilities, salinization has turned out to be a major cause for the degradation of soils (Peterson et al. 2006). Better utilization of the available moisture based on the soil type, are to be taken care off in crop enterprise considerations. Utilization of the available preserved moisture is an art that crops in drylands are adapted to possess. Water obtained during the sparse and irregular rainfall days is to be conserved in order to make it available during the moisture stress period. Water conservation measures are to be given more emphasis. Watershed-based approaches are found to be more productive in terms of water and soil conservation.

## 25.13 Conclusions

Organic farming yields more nutritious and safe food. The popularity of organic food is growing dramatically as consumer seeks organic foods that are thought to be healthier and safer. Thus, organic food perhaps ensures food safety from farm to plate. The organic farming process is more eco-friendly than conventional farming. Organic farming keeps soil healthy and maintains environment integrity, thereby promoting the health of consumers. Moreover, the organic produce market is now the fastest-growing market all over the world including in India. Organic agriculture promotes the health of consumers of a nation, the ecological health of a nation, and the economic growth of a nation by income generation holistically. India, at present, is the world's largest organic producer, and with this vision, we can conclude that encouraging organic farming in India can build a nutritionally, ecologically, and economically healthy nation in the near future.

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# Biochemical and Molecular Aspects for Plant Improvement Under Climate Stress

# 26

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## Abstract

Climate change is the most serious danger to global food security, followed by the world's population, which is expected to surpass 10 billion in the next few years. Crop development using contemporary breeding techniques, as well as effective agronomic practices using microbiome and chemical applications, is a great option to meet future global food need. To deal with the future issues of global food security, advanced breeding technologies combined with biochemical and molecular strategies can be employed to boost crop yield by producing climate-resilient superior genotypes. Recent advancements in genomic-assisted breeding (GAB) methodologies have enabled the creation of thoroughly annotated crop pan-genomes, which provide a snapshot of the whole landscape of genetic diversity (GD) and allow a species' lost gene repertoire to be recaptured. The introduction of next-generation clustered regularly interspaced short palindromic repeat/CRISPR-associated (CRISPR/Cas) methods, such as prime editing, base editing, and RNAi editing, has solidified the notion that genome editing may be used to improve crops. Furthermore, combining next-generation transdisciplinary breeding platforms can offer up new opportunities for developing climate-ready crops that contribute to global food security.

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Climate stress · Food security · CRISPR/Cas · HSP · Association mapping

## 26.1 Introduction

Climate change is the most serious concern throughout the globe nowadays. The unprecedented rise in temperature has led to an increase in conditions of drought, floods, irregular rainfall pattern, and other such happenings. Although climate change has a quite comprehensive impact on our ecosystem's productivity, it is affecting the agricultural sector at a fast speed. As climate change and agriculture are co-related very strongly and have inexplicable links, such a rapid pace of climate change has been threatening the food security (Arora 2019). Under changed climatic conditions, the major causes of crop losses are the increased biotic and abiotic stresses (Dixit et al. 2019).

As a result, it is imperative that we plan for the upcoming challenges in order to resist the unobserved effects of climate change on our agricultural systems and ensure food security. In the current agricultural setting, conventional crop-breeding techniques are insufficient to meet the expanding population's food demand. Smart and rapid crop-breeding procedures are required for generating climate-resilient crops in order to improve production and quality of agricultural produce.

The quantitative nature of abiotic stresses such as heat stress, salinity stress, and draught stress makes it difficult to develop tolerance against them using conventional methods only, and therefore, attempts have been made to identify the molecular basis of tolerance (Bakala et al. 2020). In recent years, there has been great progress in crop improvement programmes with the introduction of modernized molecular techniques such as using molecular markers. Molecular markers are simple parts of DNA which are tightly linked with the resistant gene or genes (also referred to as quantitative trait loci or QTLs) for a particular trait present on the same chromosome. After the introduction of molecular markers, these were used extensively for the mapping of genes and in other genetic approaches (Nadeem et al. 2018). Molecular-assisted selection (MAS) has been successfully applied in various crops like rice, wheat, maize, sorghum, etc. (Jena and Mackill 2008; Prasanna et al. 2010; Miedaner and Korzun 2012; Mohamed et al. 2014) for developing abiotic stress-tolerant genotypes (Rumanti et al. 2016; Devi et al. 2017). Progress in precise phenotyping and genotyping opens up a world of possibilities for generating crop varieties that are better suited to changing climatic extremes, as well as developing climate-resilient varieties/cultivars with higher yield potential (Gobu et al. 2002).

## 26.2 Climate Change and Food Security: A Global Scenario

Climate change and population growth are the two most significant threats to food security. The global population is growing at an exponential rate, increasing food consumption and putting increased pressure on agricultural lands and other related resources (Lesk et al. 2016). According to predictions, the world's population would exceed 8 billion by 2030 and 9.3 billion by 2050 (Ray et al. 2013). There is an urgent need to boost up agricultural productivity to meet the future food requirement by the end of 2050, which is 49% more than the existing value. Inconsistent pace of food production may lead to extreme hunger, famine, and social discomfort worldwide. Moreover, there are several other factors, viz. economic, social, and climatic, which are affecting the food productivity. This is a huge responsibility on the shoulder of crop breeders and policy makers to cope with massive obligation to secure food safety under shadow of climate change.

At present, climate change is the biggest threat to the humankind's existence and the environment. Climate change or global warming refers to all the changes in weather pattern as the result of natural variation and anthropogenic activity for a considerable long period. In most of the countries, agricultural production is weather dependent. Climate change has a direct impact on the productivity of physical production elements such as soil moisture and fertility, which has a detrimental impact on farming outputs and, as a result, on food security. The extreme events of climate change have accelerated the occurrence of biotic and abiotic stresses in the agricultural crops (Raza et al. 2019). The situation worsened because of fluctuations in annual rainfall and temperature, which encourage plant pathogen attacks and negatively affect crop growth. Studies have been reported that every increase in temperature by 1 °C may reduce the yield by 10–25% in major staple food crops including wheat, maize, and rice (Heeb et al. 2019; Deutsch et al. 2018). Uncertain future projection for climate change leads to crop adaptability for various stress conditions. However, for meeting the goals of sustainable development, global food security for billions of the population is only possible, if agriculture productivity is increased in a sustainable mode.

A new agricultural paradigm is required, one that includes integrated modern breeding systems, various agronomic methods, and plant microbiome assessment. Microbiomes, also known as plant-associated microorganisms, can provide critical ecosystem services, such as boosting crop development and mitigating abiotic and biotic stresses (Arif et al. 2020). Climate-smart agriculture is gaining popularity as a means of developing climate-resilient crop varieties using next-generation breeding techniques that can tolerate several stresses such as cold, heat, salinity, drought, waterlogging, and insect-pest attack, which is expected to increase the frequency of extreme weather and exacerbates the negative consequences of abiotic stressors (Lobell et al. 2011). Fundamental biological questions revolve around how plants detect stress signals and adapt to harsh surroundings. Furthermore, improving plant stress resistance is important for agricultural productivity as well as environmental sustainability, because crops with poor stress resistance consume a huge amount of water and fertilizers, putting a lot of pressure on the environment.

## 26.3 Crop Response Towards Climate-Driven Environmental Stresses

There is a complex interactive mechanism involved in plant response to the various environmental stresses during the crop growth and development phase (Fig. 26.1). Plants adapt generally two strategies, i.e. stress avoidance or stress tolerance to combat environmental stress which is directly or indirectly relatable. Stress avoidance in crops is achieved through the physiologically inactive phase, i.e. seed formation, while stress tolerance is an active reversible adjustment at cellular, molecular, and physiological levels, termed acclimatization. Acclimation to stress, on the other hand, is the result of multiple changes in gene expression that result in changes in the makeup of the plant transcriptome, proteome, and metabolome. A variety of attempts have been undertaken to develop crops that are more resistant to abiotic stress. The production of stress-resistant crops with novel and desired agronomical features is, however, one of the main impediments in modern agriculture. Therefore, it becomes more significant to understand the mechanism by which the plants sense the environmental stresses, perceive, and further transmit them to the machinery functioning at the cellular level for activation of adaptive response. The

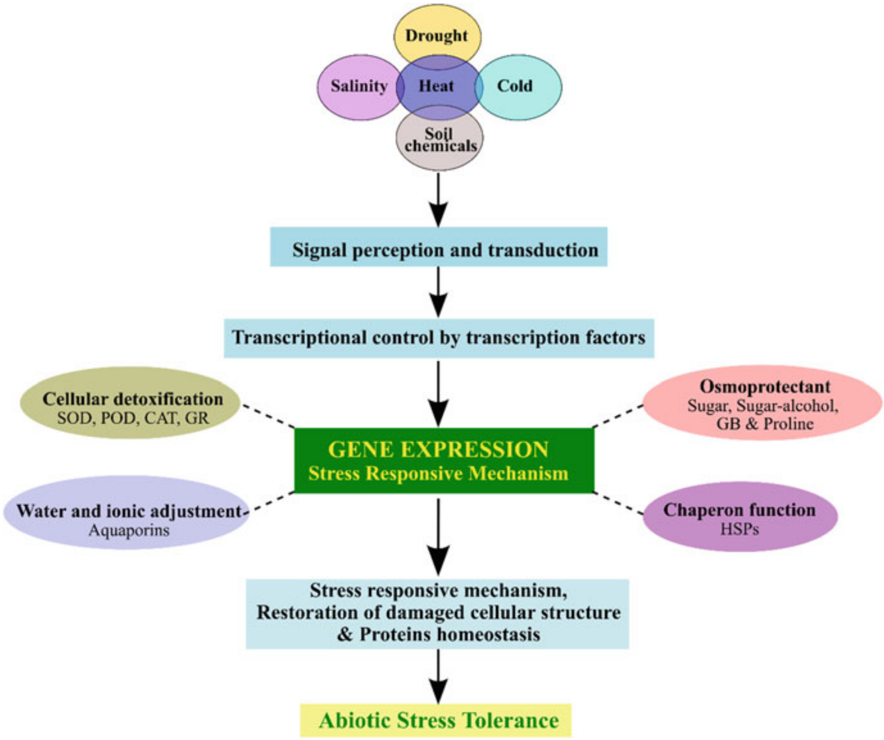

**Fig. 26.1** Schematic representation of plant responses and mechanism of tolerance under abiotic stresses

interconnection of diverse physiological, biochemical, and gene regulatory processes is crucial in the development of climate-resilient high-yielding food crop cultivars in this scenario.

### 26.3.1 Morphological Response to Abiotic Stress

Based on the environmental conditions and nutrient availability, plants regulate their growth through the root/shoot ratio (Sims et al. 2012). High root/shoot ratio indicates the plant's acclimatization under stress condition due to heat or drought to maximize the water uptake (Kwon and Woo 2016). Under water-limiting conditions, caused by heat or drought, the concentrations of amino acids, nucleosides, sugars, K, P, and N decreased in the shoot, while roots increase the same component (Gargallo-Garriga et al. 2014). These result in reduced vegetative shoot growth and more elongated and branched roots (Mangena 2020). The water-deficit condition increases the production of ROS in leaves and other vegetative parts of the plants (Jaleel et al. 2009; Mabulwana 2013). Plants have evolved a number of adaptive mechanisms to reduce transpiration as well as photosynthesis loss at the canopy level, including leaf-rolling (a change in leaf angle to reduce the surface area exposed to sunlight) (Baret et al. 2018), reduced leaf area, presence of awns, glaucousness, epicuticular wax deposition, and hairiness (Khan et al. 2018).

The other mechanism is water-use efficiency (WUE) for adaptation in the arid environment to the plants (Sun et al. 2008), where the tolerant genotypes have shown enhanced WUE with high biomass and have more deep and dense roots in comparison to susceptible genotypes (Xu et al. 2010). The plant thyme develops an extensive root system by reducing vegetative growth to survive under drought stress (Tátrai et al. 2016).

### 26.3.2 Cellular Response to Abiotic Stress

Plants detect stress stimuli at the cellular membrane level, which sets in motion a chain of processes that delivers the signal to various organelles and activates the cell's appropriate molecular complex network (Kaur and Pati 2017). Biosynthesis of cellulose and xyloglucan (the most abundant non-cellulosic component of type I primary walls) is induced in response to stress stimuli (Cosgrove 2012; Rao and Dixon 2017), which is associated with the upregulation of Ces A (cellulose synthase), XTH (xyloglucan endo-transglycosylase), and EXP (expansin), encoding genes. Under stress, a comparative investigation of alterations in the cell wall of two drought-resistant wheat varieties revealed an increase in pectin polymer RGI and RGII (rhamnogalacturonan I and II) side chains, which may lead to pectin hydrogel formation, preventing cell damage (Tenhaken 2015). Other cell wall proteins that provide strength to the cell wall, such as glycine-rich protein (GRP), proline-rich protein (PRP), and arabinogalactan protein (AGP), are similarly activated in response to abiotic stress. Reduced cell wall elasticity and extensibility, which can avoid cell collapse during water loss, is an alternate response to abiotic stress stimuli (Cosgrove 2012). Furthermore, in plants subjected to abiotic stresses, the expression of genes encoding for wall-associated kinase (WAK) proteins is occasionally upregulated, implying that stress is perceived at the cell wall or plasma membrane interface via the detection of released plant cell wall fragments (Vaahtera et al. 2019). As a result, cell wall alteration is frequently a direct response to abiotic stress and plays an important role in the plant's response.

### 26.3.3 Photosynthetic Machinery Modulation and Gaseous Exchange

On exposure to environmental stress, crop plant suffers from a number of physiological reactions including change in photosynthetic rate, nutrient uptake, photosynthate translocation, assimilation rate, water uptake, and evapotranspiration (Morales et al. 2020). Photosynthesis is a crucial physiological phenomenon affected by abiotic stress in plants (Farooq et al. 2009). Environmental stress including heat and drought negatively affects the photosystem (PSI and PS II) and reduces photosynthesis activity along with chlorophyll biosynthesis and electron transport system. Abiotic stress may also lead to RuBp (ribulose 1,5-bisphosphate) degeneration and thus affects RuBp activity due to limitation in $CO_2$ diffusion factors or sometimes metabolic factors. Several studies have emphasized the role of stomata movement during stress conditions leading to a reduction in $CO_2$ assimilation through declined sub-stomatal wall and chloroplast $CO_2$ (Ci and Cc, respectively) concentration.

In plants, ambient $CO_2$ diffuses into the intercellular space through stomata (i.e. stomatal limitation) and subsequently across the mesophyll (mesophyll limits) at the carboxylation site. Abiotic stress affects the chloroplast's photosynthetic pigments and thylakoid membranes (Anjum et al. 2011). Drought-induced reductions in chlorophyll content have been seen in wheat, maize, rice, and other crops. The concentration of chlorophyll a was larger than that of chlorophyll b in drought-stressed *Brassica* plants, with a drop in the chlorophyll a/b ratio. Reduced chlorophyll accumulation in plants under high-temperature stress can be caused by decreased chlorophyll production, increased degradation, or a mix of the two. The inactivation of different photosynthetic enzymes under high-temperature stress is thought to be the cause of chlorophyll synthesis inhibition. The activity of 5-aminolevulinate dehydratase, a key enzyme in the pyrrole biosynthesis pathway, decreased drastically in wheat when it was exposed to heat.

### 26.3.4 Osmotic Adjustment and Osmoprotectants

Environmental stress including drought and heat stress cause intracellular water loss and impose osmotic stress on plants. Plants accumulate specific compounds to counter osmotic disturbance during stress conditions without disturbing the chemical balance in the cell. Sucrose, fructose, trehalose, sugar alcohols, polyamines, malate, oxalate, quaternary ammonium compounds, and a variety of other organic solutes are referred to as osmoprotectants. Proline and glycine betaine (GB) are quaternary ammonium osmoprotectants that accumulate in large amounts in plants in response to diverse stresses. A significant link between proline deposition and plant tolerance to diverse abiotic stressors has been found in several independent investigations (Kavi Kishor and Sreenivasulu 2014). Furthermore, exogenous proline administration has been found to be an effective way to improve plant stress tolerance (Hayat et al. 2012). GB is another important chemical that aids in osmoprotection, stroma adjustment, and thylakoid membrane protection in order to keep photosynthetic activity going even in stressful situations (Tian et al. 2017). GB shields Rubisco from heat-induced instability and safeguards the photosystem II (PS-II) complex. Enhanced GB accumulation is critical for abiotic stress resistance in various agronomically important crops, including tomato, potato, maize, barley, and tobacco (Iturriaga et al. 2009).

### 26.3.5 Oxidative Damage and ROS (Reactive Oxygen Species) Regulation

The majority of abiotic stressors result in oxidative damage in plants (Fig. 26.1). Abiotic stressors, such as heat, drought, and salinity, cause oxidative damage in plants by forming a cascade of reactive oxygen species (ROS). By destroying lipids and proteins, ROS pose a major threat to the cell's ability to function. ROS are mostly produced in the chloroplast of the cell organelle, but they are also produced in mitochondria when oxygen reacts with electron transport chain components (Reddy et al. 2004). The mechanisms for ROS generation can be either enzymatic or non-enzymatic in cells. The most studied enzymatic source of ROS in plant is NADPH oxidases which are also referred to as respiratory burst oxidase homologs (RBOHs). The activity of plant NADPH oxidase is regulated by some key regulatory components including $Ca^{2+}$, calcium-dependent protein kinases (CDPKs), $Ca^{2+}$/CaM-dependent protein kinase, and some small GTPases. In barley, apoplastic ROS generation through NADPH oxidase in the xylem parenchyma tissue is a critical factor for tolerance in plants against salt stress.

Antioxidants, which can be enzymatic or non-enzymatic, are the most effective defensive mechanism in plants against ROS production. Superoxide dismutase (SOD), glutathione reductase (GR), guaiacol peroxidase (POD), and catalase (CAT) are some of the primary enzymes involved in this system (Farooq et al. 2009). Superoxide ions produced by NADPH oxidase are transformed to hydrogen peroxide ($H_2O_2$) and catalysed by various superoxide dismutase (SOD) enzyme isoforms. Hydrogen peroxide regulates osmotic adjustment, photosynthesis, ROS detoxification, and phytohormone signalling, all of which contribute to stress tolerance. These antioxidant enzymes are found in plant cells at various locations and work together to detoxify produced ROS. Along with these enzymes, non-enzymatic components such as carotenoids and glutathione can play an important part in the antioxidant defence system. As a result, maintaining larger levels of anti-oxidants can be an effective strategy for plants to combat the detrimental effects of ROS (Sharma and Dubey 2005). Many studies have shown that pre-treating seeds with H2O2 causes an inductive pulse that helps protect plants from abiotic stresses by restoring redox homeostasis and reducing oxidative damage to membranes, lipids, and proteins via altering stress signalling pathways. Phytohormones are natural defensive chemicals found in plants that help them sustain higher levels of antioxidants in stressful situations. By arbitrating growth, development, source/sink transitions, and nutrient allocation, these hormones aid plants in acclimating to adverse situations (Fahad et al. 2015).

## 26.4 Plant Molecular Chaperones

Proteins are structurally more diverse and functionally most complex macromolecules. Since the beginning of the study of proteins, it remains elusive to the scientific community how complex a protein molecule folds into its different structural hierarchy and the factor responsible for its proper folding. Later it was found that the protein folding information lies in the protein backbone. But many proteins were found to be synthesized and remained in their native forms (Bartlett and Radford 2009). The basic concept of chaperon started while working with plant enzyme Rubisco, where it was found that the activity of enzyme decreases in isolated chloroplast. This brings up the idea that transient binding of large subunits with other proteins might be an important step in the activity of the enzyme (Barraclough and Ellis 1980). Before this, there was some evidence for the assembly of protein, but a notion of self-assembly of protein was prevalent during that time. R. A. Laskey and his colleagues were the first who used the term "molecular chaperon" while working on nucleoplasmin, an acidic protein required for the assembly of the nucleosome (Laskey et al. 1978). Work with nucleoplasmin and Rubisco suggested that the role of binding protein is essential to prevent the free surface of the protein by masking them. Pelham (1986) reported the widespread presence of heat shock protein (HSP70) in plants and microorganisms. They were involved in the assembly and disassembly of proteins in the cytosol and endoplasmic reticulum. He also suggested that these proteins are required in protein folding and assembly in normal cells and are required in large amount when proteins have been damaged by stress.

Chaperones help other proteins fold correctly during the translation or post-translation step, during renaturation, and in some cases, during transfer of the proteins to their destined locations. Some chaperones also act like proteases (Deuerling and Bukau 2004). The expression of chaperones increases during stress; therefore, for this reason, chaperones are considered as a heterogeneous group of proteins, termed heat shock protein (HSP).

### 26.4.1 Classification of HSPs

HSPs are ubiquitous (present in all cell tissues) and promiscuous. Within a cell in eukaryotes, chaperones occur in different organelles like cytoplasm, mitochondria, and chloroplast, whereas in cytoplasm and periplasm in prokaryotes (Jackson-Constan et al. 2001). The family members of chaperones, like HSP100s, HSP90s, HSP70s, HSP60s, and sHSPs, have now been identified and characterized for their role.

#### 26.4.1.1 HSP100 Family

HSP100 chaperones are a member of a large group of AAA+ ATPase families. Molecular weights of this class of HSPs range between 100 and 104 kDa and are involved in the reactivation of misfolded proteins by ATP-dependent basis (Kim et al. 2007). Expression of this class of HSPs increases by many folds under stress conditions. HSP100s are thoroughly studied for their role in providing tolerance to plants against heat stress (Hong and Vierling 2001; Lin et al. 2014). Some of the members of this group work as a housekeeping protein which is essential for chloroplast development (Lee et al. 2007). HSP100 is associated with sHSP in re-solubilizing protein aggregates (Bösl et al. 2006). Lin et al. (2014) reported positive feedback between sHSP and HSP100 in providing heat acclimation in rice seedlings. Structural analysis of HSP100 reveals the presence of three domains, namely, the nucleotide-binding domain, middle domain, and second nucleotide-binding domain. HSP 100 family can be further divided into two groups: in one group, there are two nucleotide-binding domains, whereas, in the other, there is only one nucleotide-binding domain. The binding of ATP to the N-terminal domain stabilizes its oligomeric state. HSP 100 recruits another protein, HSP70/DnaK, to disaggregate proteins. This family's precise mechanism of action is not known, but it is considered that HSP100 solubilizes the aggregated protein and transfers it to the HSP70 system for its proper refolding (Goloubinoff et al. 1999).

#### 26.4.1.2 HSP90 Family

HSP90 is the most abundant (1–2% of total cell protein) heat shock protein synthesized in the cytoplasm of both prokaryotic and eukaryotic cells, and its expression is upregulated under stress conditions. HSP90 protein functions as a dimer. The molecular weight of members of the family of HSP90 ranges between ~80 and 94 kDa. HSP90s are highly conserved and function in an ATP-dependent method. They play a crucial role in folding a wide range of proteins, including signalling proteins, transcription factors, regulatory kinases, and cell cycle regulators (Echeverria and Picard 2010; Gupta et al. 2010). Structural analysis reveals the presence of a highly conserved ATPase domain at the N-terminal, middle domain, and dimerization domain at the C-terminal. It also contains a flexible arm connecting between the middle and N-terminal domains and a C-terminal domain with a conserved motif that interacts with the tetrapeptide repeat domain of co-chaperones. HSP90 does not act on a nascent protein; rather, it acts on a target protein of near-native conformation (Young et al. 2001). It is a key component for

26S proteasomal complex assembly and maintenance (Imai et al. 2003). Members of HSP90 are a key regulator of normal growth and development in *Arabidopsis* and *Nicotiana benthamiana* (Sangster and Queitsch 2005; Sangster et al. 2007). The loss of HSP's function altered plant phenotype, including morphological changes and losses in plant immunity (Kadota and Shirasu 2012). Cytosolic R protein, containing leucine-rich repeat, was activated by HSP90, which mediates defence against many microbial pathogens (Shirasu 2009). Cytosolic HSP90 and its co-chaperone Hop/Sti1 participate in antifungal immunity (Chen et al. 2010).

#### 26.4.1.3 HSP70 Family

HSP70 proteins function as a chaperon for the newly synthesized proteins to prevent their aggregation in an ATP-dependent manner and also help in their movement to the final location. Most of the members of this family are constitutively expressed, and their expression increases under stress. In prokaryotes, the homologs of HSP70 are HscA, DnaK, and HscC protein. HSP70 works in association with another chaperon HSP40 (also known as DnaJ) family (Mayer 2010; Kampinga and Craig 2010). Structural analysis of HSP70 family protein reveals the presence of two functional domains: the N-terminal having ATPase domain and a C-terminal domain peptide binding domain, which contains peptide-binding domains. The C-terminal segment contains an α-helical lid segment (binding site for adenosine residue) and β-sandwich subdomain (recognizes a segment of seven residues of hydrophobic amino acid) (Mayer 2010; Rüdiger et al. 1997). Opening and closing of the α-helical lid segment depend on the kind of adenosine phosphate molecule bound to the lid. In an ATP-bound state the lid remains open and closes at ADP-bound state. During ATP-bound state, folding peptide binds and releases rapidly, while at ADP-bound state, the substrate proteins are bound very tightly to the peptide-binding domain (Mayer et al. 2001). HSP70 member proteins are confined in the cytoplasm, endoplasmic reticulum, mitochondria, and other organelles. Al-Whaibi (2011) reported that HSP70 works in cooperation with sHSP members as reported in *Pisum sativum*. HSP70 plays a crucial role in abiotic stress management by targeting unstable proteins to lysosomes or proteasome (Hartl 1996). Morimoto (1998) reported that the HSP70 family regulates the biological activity of an organism and functions as a negative repressor of transcription of heat shock transcription factor (HSF). The binding of HSF to heat shock elements is prevented by the trimerization of HSP70. Thus, the transcriptional activation of HSF-regulated transcriptional heat-responsive genes is repressed (Kim and Schöffl 2002). Furthermore, they have also been linked to the modulation of various signal transducers like protein kinases and protein phosphatase (Ding et al. 1998).

#### 26.4.1.4 HSP60 Family

HSP60 is another class of HSP and is also called chaperonins. The bacterial homologs of HSP60 are known as GroEL. They play a major role in assisting the protein folding of the newly synthesized protein. This class of chaperones is ubiquitously present in the cell but abundant in chloroplast and mitochondria. Based on structural organization, chaperonins are further subdivided into two subfamilies: group I and group II chaperonins. Group I chaperonins present in eukaryotes (HSP60 in mitochondria and Rubisco binding protein in the chloroplast) and bacteria (GroEL) have the seven-membered ring. It interacts with HSP10 proteins. Group II chaperonins are consist of eight to nine subunits per ring and are organized to form hetero-oligomeric ring complexes. Group II chaperonins consist of “t-complex polypeptide 1” (Wang et al. 2004). GroEL interacts with proteins having complex α/β or α+β domain topologies (Fujiwara et al. 2010). The substrate binds with hydrophobic amino acid residues at the ring centre of the GroEL. The binding of the substrate to the GroEL leads to a conformational change forming a cage-like structure. A net-negatively charged hydrophilic inner wall characterizes this cage-like structure. Conformational change in GroEL induces GroES binding in an ATP-dependent manner (Hartl and Hayer-Hartl 2009; Horwich and Fenton 2009). Encapsulated protein in GroEL- GroES is free to fold and leaves the system after GroES dissociates from GroEL (Brinker et al. 2001).

#### 26.4.1.5 HSP40 Family

Members of the HSP40 family are also called DnaJ and are co-chaperones for the HSP70 family (Kampinga and Craig 2010). J-domain (∼70 amino acids) interacts with the nucleotide-binding domain of HSP70. In the J domain, helices II and III are antiparallel in orientation and packed tightly. Helices are joined by a loop having a highly conserved HPD (histidine, proline, and aspartic acid residues) motif (Walsh et al. 2004). Structural analysis has also shown the presence of an additional structure: a G/F (glycine/phenylalanine) region, which links the J-domain and zinc finger motif and has a role in the stability of the J-domain (Rajan and D’Silva 2009). A zinc finger motif is a central region of HSP40 and contains four CXXCXGXG repeats in two separate clusters, and each cluster is associated with a zinc ion (Walsh et al. 2004). The last part is the C-terminal region, which is important in the dimerization and chaperone function. HSP40 is important in maintaining cellular physiology. HSP40 is important for HSP70 activity by regulating the housekeeping and stress-related activity of HSP70. HSP40 prevents the substrate peptide from aggregation (Christen and Han 2004).

#### 26.4.1.6 sHSP Family

These are small molecular weight peptides ranging from 16 to 40 kDa. These are the most abundant HSPs present among all forms of HSPs. In higher plants, there are around 20 different sHSPs. sHSPs are characterized by the presence of variable N-terminal domain followed by conserved C-terminal domain and C-terminal extension. sHSPs are present in oligomeric form, and the number of oligomers among different sHSPs varies greatly (Banerjee and Roychoudhury 2018). sHSPs perform their chaperone activity in an ATP-independent manner (Basha et al. 2013). Poulain et al. (2010) reported a hexameric disk in a barrel-shaped structure in sHSP16.9. In higher plants, based on their presence within a cell, sHSPs are grouped into 11 subfamilies, namely, MTI, CI-CVI, ER, MTII, CP, and PX (Waters 2013). The expression of sHSPs in plants upregulates in heat stress and other abiotic stresses. Their expression in various plant organs and at different developmental stages signifies their diverse nature and adaption to the different stresses (Sun et al. 2002; Al-Whaibi 2011; Koo et al. 2015). Members of this family also perform another activity: they are involved in the protein degradation of misfolded protein. sHSP binds to the misfolded proteins through hydrophobic interaction, preventing their aggregation (Al-Whaibi 2011). Recent studies have shown that purified sHSP from plants interacts with denatured protein and helps in subsequent refolding in cooperation with ATP-dependent chaperones such as HSP40/HSP70 and HSp100/ClpB complexes (Muthusamy et al. 2016).

| Family | Molecular size (kDa) | Chaperones | Location | Function | References |
|---|---|---|---|---|---|
| HSP100 | 100–104 | HSP100, Clp | Cytosol (Hsp101 (Hsp102); Hsp104; Hsp105 alpha and beta; Hsp110)<br>Mitochondria (ClpXP/ Hsp100)<br>ER (Hsp170 (Grp170)) | Resolubilize heat-inactivated protein aggregates, proper protein folding, protein degradation | Hong and Vierling (2001) and Bösl et al. (2006) |
| HSP90 | 81–99 | HSP90, Grp94/ gp96 | Cytosol (Hsp90 (Hsp82; Hsp83; Hsp90 alpha and beta); Grp94)<br>ER (Hsp90 (GRP94; Grp94; endoplasmin; gp96))<br>Chloroplast (Hsp93 (atHsp93-III)) | Proper protein folding, regulation of receptor protein | Hubert et al. (2009), Kadota and Shirasu (2012), and Bao et al. (2014) |
| HSP70 | 65–80 | HSP70, BiP/Grp78 | Cytosol (Hsp70 (Hsp72); Hsc70 (Hsp73); SSA1-4; SSB1-2)<br>ER (BiP (Grp78); Erp72; SSi1p; Kar2p)<br>Mitochondria (mhsp70; SSC1; | Role in folding of nascent polypeptide chain, refolding of denatured proteins, protein translocation | Kanzaki et al. (2003), Kampinga and Craig (2010), and Park et al. (2009) |

(continued)

| Family | Molecular size (kDa) | Chaperones | Location | Function | References |
|---|---|---|---|---|---|
| | | | mtHsp70 (Grp75); Hsp78; Ssq1)<br>Chloroplast (Hsp70 (DnaK) Hsp70B) | | |
| HSP60 | 55–64 | | Mitochondria (Cpn60 (mtGroEL; mtHsp60))<br>Chloroplast (Cpn60 (Rubisco binding protein)) | Prevents protein aggregation, helps in refolding of misfolded protein, protein degradation | |
| HSP40 | 35–54 | HSP40, ERdj | Cytosol (Hsp40; Hdj1 (MAS5); Hdj2 (DjA1; HSDJ); DjA4; Sis1p; Ydj1p)<br>ER (Hsp40; Hsp47; Sec63p; Erdj3; Scj1p; JEM1p) | Important co-chaperone of HSP70 | Guo and Snapp (2013) and Ohta and Takaiwa (2014) |
| sHSP | 15–30 | HSP20 | Cytosol (alpha-crystallin family; Hsp10; Hsp20 (Hsp26); Hsp22; Hsp27)<br>ER (Cpn20)<br>Mitochondria (Hsp10 (Cpn10; mtGroES)) | Act as co-chaperons for HSP100 and HSP70, prevent misfolding of protein against heat stress | Kotak et al. (2007) and Liberek et al. (2008) |

## 26.5 Molecular Breeding Methods

Molecular crop breeding assisted with molecular markers has brought revolution in the field of plant genetics studies. Marker-assisted selection (MAS) can be used to enhance the efficiency of plant breeding by means of precise transfer of genes related to the trait of interest. The success rate of MAS generally is influenced by the number of genes to be transferred and the distance between the flanking markers with the target gene. Marker-assisted selection (MAS), marker-assisted backcrossing (MABC), and marker-assisted recurrent selection (MARS) approaches are used to select stress resilience genotypes using the markers associated with desirable traits (Varshney et al. 2012). MAS has been used for breeding of crops like rice, wheat, barley, maize, sorghum, etc. (Cobb et al. 2019). Quantitative trait loci (QTL) mapping has been used for characterizing quantitative traits by identifying the QTLs with the help of DNA markers (Das et al. 2017). In rice, marker-assisted foreground breeding (MAFB) was used for stacking of genes responsible for stress resilience to abiotic stress like submergence (Khan et al. 2013) and salinity (Das and Rao 2015), while a combination of MAFB and MABC was followed for introgressing three QTLs, viz. qDTY1.1, qDTY2.2, and qDTY4.1, for enhancing tolerance against reproductive stage drought (Janaki Ramayya et al. 2021). It has been observed in some cases that resistance imparted by single gene can be overcome in a few years (Borrelli et al. 2018; Lv et al. 2020). Therefore, it is the need of the hour that for sustainable crop improvement programmes under different climatic conditions, multiple genes for resistance against a particular trait should be integrated (Srivastava and Thomson 2016). Gene pyramiding using closely related markers has hastened the generation of lasting tolerance with excellent precision in less time against various abiotic stress conditions such as drought, cold, salinity stress, and submergence in wheat, maize, and cotton (Shamsudin et al. 2016; Pradhan et al. 2015; Suh et al. 2015). In rice, genes/QTLs for submergence tolerance (Sub1) and salinity tolerance (Saltol) were merged in a rice variety called "CRMAS2621-7-1" to create a new variety called "Improved Lalat" (Das and Rao 2015).

### 26.5.1 QTLs for Drought Stress Tolerance

QTLs for water stress have been identified in a variety of crops, including mustard (Hall et al. 2005), maize (Landi et al. 2007), barley (Teulat et al. 2002), rice (Atkinson et al. 2015), and pearl millet (Bidinger et al. 2007).

#### 26.5.1.1 Wheat

Introgression of drought-tolerant QTLs can be effective to combat the moisture stress in wheat. Several studies highlighted the role of chromosome 4A in drought tolerance of wheat crop (Alexander et al. 2012). There have been many investigations for identification of QTLs for various physiological and photosynthetic parameters, viz. high efficiency of water use, deep root-to-shoot ratio (Spielmeyer et al. 2007; Hamada et al. 2012), root length (QRl.ccsu-2B.1), and root dry weight (QRdw.ccsu-2A.2 and QRdw.ccsu-2A.1) (Bharti et al. 2014) on chromosomes 2B and 2A. Further, their association with relative water content (QCMSa2AC) (Malik et al. 2015), net photosynthetic rate (QPn2AC), and cell membrane stability (QCMSa2AC) also have been reported. Gahlaut et al. (2017)

conducted QTL interval mapping for nine drought-responsive agronomic traits in a doubled haploid mapping population and found that out of 98 QTLs, 32 affected drought sensitivity indices.

#### 26.5.1.2 Rice

Drought stress is a major constraint affecting rice yield negatively. Selamat and Nadarajah (2021) recorded 653 QTLs from 27 genetic maps that responded to drought. From this study, they identified 70 meta-QTLs (MQTLs) and mapped 453 QTLs into these meta-QTL areas. The meta-QTLs derived and the genes identified can be used effectively in molecular breeding for drought resistance in rice.

#### 26.5.1.3 Sorghum

Stay-green phenotypes in sorghum are linked to drought tolerance after flowering. Four significant QTLs for stay-green (*stg*) traits, *Stg1*, *Stg2*, *Stg3*, and *Stg4*, have been identified and have been mapped along with *Stg1* and *Stg2* discovered on the 3rd chromosome (Harris et al. 2006; Xu et al. 2012), while Stg3 was mapped on the 2nd chromosome and Stg4 was mapped on the 5th chromosome (Harris et al. 2006).

#### 26.5.1.4 Barley

Drought and salinity are the two major abiotic stresses that rigorously reduced barley production at a global scale. Fan et al. (2015) used 72 double haploid lines in barley for identifying drought and salinity tolerance QTLs. Two QTLs for drought tolerance were identified (i.e. leaf wilting under drought stress) along with one QTL with salinity tolerance.

#### 26.5.1.5 Cotton

Three QTLs (qtlRWC1, qtlWC-2, qtlELWL) lessen water loss and high relative water content (RWC) under drought stress conditions (Saleem et al. 2015).

#### 26.5.1.6 Common Bean

For QTL analysis, an improved genetic map was generated by Diaz et al. (2018) for drought tolerance, in which a total of 339 markers was added including RAPD (2), AFLP (53), SNP (127), and microsatellite (42). However, only 143 QTLs were identified among all chromosomes for all studied traits, while consistent yield QTL was identified only with the 4th chromosome.

### 26.5.2 QTLs for High-Temperature Stress Tolerance

#### 26.5.2.1 Wheat

For mapping QTLs for heat tolerance and related attributes, viz. decrease in canopy temperature (Pinto et al. 2010), plant senescence (Vijayalakshmi et al. 2010) along with carbon isotope discernment (Rebetzke et al. 2008) has been studied.

#### 26.5.2.2 Rice

In rice, the yield and quality during the flowering stage is affected to a great extent by heat stress. Chen et al. (2021) while mapping QTLs for heat tolerance using F2:3 populations reported a new major QTL (qHTT8) on chromosome 8. There are 65 replicated genes that have been reported in the candidate region of qHTT8, where genes related to heat tolerance were only 10. Several QTLs for senescence under heat stress were found by Vijayalakshmi et al. (2010). Four QTLs mapped by Ye et al. (2012, 2015) (qhr1, qhr3-1, qhr4-3, and qhr8-1) were associated with heat stress tolerance during flowering stage along with two minor QTLs associated with spike fertility in rice during gametogenesis including qHTSF1.1 and qHTSF4.1.

### 26.5.3 QTLs for Low-Temperature Stress Tolerance

Many crops and other wild relatives, viz. including lentil (Kahraman et al. 2004), maize (Presterl et al. 2007; Revilla et al. 2016), ryegrass (Zhang et al. 2009), sorghum (Knoll and Ejeta 2008), and faba bean, have low-temperature tolerant genes and QTLs that can be used in crop improvement through molecular marker breeding tools for cold stress tolerance (Sallam et al. 2016).

#### 26.5.3.1 Rice

Among cereals, cold stress severely affects the rice production. For cold stress tolerance in rice breeding programme, gene pyramiding of QTLs using MAS is useful (Shinada et al. 2014). By utilizing wild rice for transferring genes for cold tolerance, there will be broadening of genetic base, which in turn can enhance rice production (Xie et al. 2012). Zhou et al. (2010) and Kuroki et al. (2007) mapped QTLs (qCTB7 and qCTB8) which were related to low-temperature stress tolerance during the booting period, while Kuroki et al. (2007) (qSCT-3-1), Wang et al. (2011) (qCTS8.1), and Andaya and Tai (2003) (qCTS12, qCTS4) mapped QTLs at seedling stage which were associated with tolerance to cold-induced wilting and growth recovery following cold stress damage. Das et al. (2017) found a Ran gene, OsRAN1, which is thought to be important for breeding of low-temperature stress-tolerant varieties.

#### 26.5.3.2 Maize

Hu et al. (2016) identified QTLs linked to low-temperature germination and primary root length on chromosomes 4, 5, 6, 7, and 9. The qCTR5 and qCTR12 are the two QTLs present at 5th and 12th chromosomes found to be responsible for managing male sterility caused by low temperatures, according to Koumoto et al. (2016).

#### 26.5.3.3 Barley

Frost tolerance QTL (QFr-H1) was mapped by Reinheimer et al. (2004).

### 26.5.4 QTLs for Salinity Stress Tolerance

High salinity in soil is a serious abiotic environmental stress experienced by the crops during growth and development. This affects the production potential of cereal crops. To develop salt-tolerant varieties, QTL mapping may prove to be a helpful approach in different crops (Hossain et al. 2015) including maize (Wang et al. 2012) and barley (Sbei et al. 2014).

#### 26.5.4.1 Wheat

According to Dubcovsky et al. (1996), on chromosome locus 4D called "kna1" regulates the ion ratio of $K^+/Na^+$ in wheat photosynthetic unit (leaves), linked to salinity tolerance. A quantitative trait locus governing sodium ion exclusion (Na+) was mapped on chromosome 2A (Genc et al. 2010; James et al. 2013), while a QTL controlling Cl- concentration was mapped on chromosome 5A (barc56/gwm186) (Genc et al. 2014).

#### 26.5.4.2 Rice

Although salinity stress in rice has been observed at all stages of crop growth, seedling development and reproductive stages are more vulnerable (Thitisaksakul et al. 2015). The QTL mapping using microsatellites may also be helpful for the development of salt-tolerant rice varieties, having gene expression responsible for salt tolerance (Hossain et al. 2015; Tiwari et al. 2016; Bimpong et al. 2016). Das et al. (2015) reported that a salt-tolerant variety, Nona Bokra, that conserves homeostasis of $K^+$ under conditions of soil salinity was mapped with SKC1. A QTL (qNaSH8.1) responsible for controlling $Na^+$ content under severe soil saline conditions was mapped by Pandit et al. (2010), whereas another QTL (qNar/Kr5) for $Na^+$ and $K^+$ ratio was found by Ahmadi and Fotokian (2011) in roots of rice plant. Anh et al. (2016) found ten QTLs for salinity stress tolerance on the 1st, 3rd, 4th, 6th, 7th, and 9th chromosome. QTL named "Saltol" for salt tolerance in rice was identified by Ganie in 2016.

### 26.5.5 QTLs for Water Lodging Stress Tolerance

Water lodging affects the production and quality of cereal crops by causing damage to the stem like breakage or banding (Verma et al. 2005; Zhang et al. 2016); however, little research work has been carried out on this stress problem. This trait can be improved by utilizing the responsible resistance genes.

In many cereals such as like barley (Hayes et al. 1993; Backes et al. 1995), rice (lrt5) (Ishimaru et al. 2008), maize (Flint-Garcia et al. 2003), and oat (De Koeyer et al. 2004), QTLs have been reported for water lodging stress.

### 26.5.6 QTLs for Water Submergence Stress Tolerance

In comparison to water lodging stress, submergence stress is even more harmful as it can cause huge yield losses (Ahmad et al. 2018). Submergence QTL (SUB1) in rice was mapped by Toojinda (2003). Xu et al. (2006) reported three QTLs (SUB1A, SUB1B, and SUB1C) after fine mapping the SUB1 QTL. It was discovered that using the SUB1A QTL in rice can result in a high level of submergence tolerance (Singh et al. 2014). A large QTL on the 9th chromosome provides in totality tolerance toward submergence stress in rice for up to 14 days or more (Septiningsih et al. 2009). On chromosome 6, a submergence-related QTL (Subtol6) in maize was identified by Campbell et al. (2015).

## 26.6 Omics Techniques for Crop Improvement

Omics encompasses a wide range of approaches for classifying and measuring the functions and connections of various molecules in an organism. These techniques include transcriptomics (Varshney et al. 2005), proteomics (Pandey et al. 2008), and metabolomics (Razzaq et al. 2019). Omics approaches can improve agricultural productivity by finding candidate genes and distinct pathways connected to diverse abiotic and biotic challenges by merging genomics data with phenotypic information (Langridge and Fleury 2011), and this integration will ensure the evolution of crop breeding from genomics-assisted breeding (GAB) to omics-assisted breeding (OAB) in the years ahead.

### 26.6.1 Transcriptomics

For targeted gene sequencing, transcriptome sequencing is a more appealing approach, currently used in a range of functional genomics methodologies, such as gene expression profiling, genome annotation, and non-coding RNA identification, to name a few (Morozova and Marra 2008). Different functional markers (EST-SSRs, SNPs) and intron-spanning regions (ISRs) are obtained utilizing transcriptome assemblies created using various sequencing techniques for subsequent application in crop development programmes (Pandey et al. 2016). Additionally, the gene expression profile data collected from these assemblies can be used to identify candidate genes connected to various abiotic stressors.

### 26.6.2 Proteomics

Proteomics is the study of cellular proteomes, which is the study of a biological unit’s set of distinct proteins during a certain developmental stage (Jorrín et al. 2006). Proteomics is being employed in plants to investigate stress response features and processes. As a result, the proteomics data gained is combined with genetic data for the trait of interest in order to design advanced crop development strategies (Vanderschuren et al. 2013). Two of the most essential components of plant proteomics are proteome mapping and comparing protein profiles for different genotypes under stress conditions (Hu et al. 2015; Katam et al. 2015).

### 26.6.3 Metabolomics

Metabolomics is a novel way to investigate multiple metabolic networks at a certain stage of development in a specific cell/tissue/organ that are associated with plant biotic and abiotic stress tolerance (Arbona et al. 2013). Latest metabolomics tools including novel chromatographic and spectroscopic techniques allow to detect, identify, assess, and evaluate various metabolites effectively (Sauer et al. 2017). The implementation of metabolic QTL-assisted breeding could lead to a better understanding of the function of particular genes of interest, as well as their usage in crop screening and breeding (Tugizimana et al. 2018; Agarrwal and Nair 2020).

## 26.7 QTL Analysis-Based Breeding with Advanced Backcross (AB-Breeding)

The molecular breeding methodologies MABC and MARS are only beneficial when superior alleles for the trait of interest are present in the breeding germplasm collection. However, genetic heterogeneity for a given characteristic may not always be present in the core gene pool. In such circumstances, advanced-backcross QTL-based breeding (AB-breeding) is the ideal means of introducing novel alleles from wild relatives to farmed species. Backcrossing of the cultivar with selected wild species is done first in the AB-breeding strategy. Then, in a segregating population like BC2F2 or BC2F3, selection is done to find the progeny with the desired features. Both genotyping and phenotypic data collected with this segregating population will be subjected to QTL analysis in order to find QTLs and related markers. In short, the AB-QTL technique comprises simultaneously detecting and transferring favourable QTL from un-adopted germplasm into selected breeding lines (Tanksley and Nelson 1996).

## 26.8 Genomics-Assisted Breeding (GAB)

The integration and application of genomic tools to breeding techniques in order to develop superior lines with increased abiotic stress tolerance is known as genomic-assisted breeding. GAB's purpose is to establish and exploit the genotype-phenotype relationship. With the advent of next-generation sequencing (NGS) (Varshney et al. 2009) and high-throughput genotyping technology (Varshney 2011), genome-wide marker profile/allele data may now be utilized to predict progeny phenotype. Over the last two decades, the availability of molecular markers such as simple sequence repeats (Gupta and Varshney 2004) and SNPs has made it easier to untangle intricate characteristics using QTL mapping and genome-wide association mapping approaches (Varshney et al. 2015). GAB has been particularly successful in cereals (Septiningsih et al. 2013) and legumes for a variety of reasons (Varshney 2016; Pratap et al. 2017).

## 26.9 Next-Generation GAB Approaches

When low-cost genotyping/sequencing and diagnostic markers become more widely available, we anticipate that genomic selection and genome editing technologies will be used in next-generation GAB approaches.

### 26.9.1 Genomic Selection (GS)

Marker-assisted breeding approaches like MABC and MARS are very effective for simple inherited traits but can be difficult to apply for polygenic traits like abiotic stresses. Such polygenic traits are controlled by multiple genes/QTLs which may exhibit epistatic interactions, thereby showing some altered expression of traits. But these problems can be overcome by using a novel approach, “genomic- selection”, which is quite easy and reliable (Deshmukh et al. 2014). GS identifies small-effect QTLs which control most of the variation including epistatic interaction effects. GS is an effective approach as different prediction models are developed for predicting the breeding values of better genotypes based on all marker information (Heffner et al. 2009). It relies on marker-based selection that might be performed even prior to marker × trait associations. GS is being used for breeding climate-resilient crops nowadays which can result into enhanced yield levels by shortening the breeding cycles.

### 26.9.2 Genome Editing

The exchange of genetic material through natural mechanisms is hindered in several crop species due to genetic obstacles such as ploidy discrepancies, and hence the tremendous genetic variation found in crop’s wild relatives stays untapped and unused. Genome editing, a technique for altering specific genomic regions, may be better suited to improve one or two traits in popular kinds (Scheben et al. 2017). It is an important component in breeders’ toolkit that has shown huge potential in revolutionizing the crop improvement. Recently emerging genome or gene editing technologies include either a site-specific recombinase (SSR) or a site-specific nuclease (SSN) system (Abdallah et al. 2015). The SSR system depends on recombinase family and induces high frequencies of homologous recombination. Zink finger nucleases (ZFNs), RNA-guided endonucleases (RNA-guided endonucleases), transcription-activator-like effector nucleases (TALENs), and

CRISPR (cluster of regularly interspaced palindromic repeats) are all part of the SSN system, which activates endogenous DNA repair pathways (Wang et al. 2017; Bakala et al. 2020). Out of these different approaches, CRISPR is being used on a large scale due to its tremendous potential in crop breeding and improvement programmes (Kim 2016). Gene editing approach is more precise than conventional crop-breeding methods. It has been found to be effective for improving crops for unfavourable weather conditions in addition to enhancing their nutritional values. There are numerous examples of better plant varieties developed utilizing genome editing technology, and 37 those very examples have recently been fully documented in *Arabidopsis*, tobacco, maize, rice, wheat, canola, soybean, tomato, and cucumber (Kamburova et al. 2017). It has been used in maize for developing drought stress resistance by replacing the promoter of a gene AGROS8 (Shi et al. 2017).

## 26.10 Phenomics and Artificial Intelligence (AI)

Advanced genomes and phenomics approaches have generated massive amounts of data. The link between genotype and phenotype is not always linear, and minor changes at one level may have a greater influence at a higher level (Bakala et al. 2020). For identification and proper understanding of complicated biological interactions with the help of large-scale genomics and phenomics data, next-gen AI seems to be important (Harfouche et al. 2019). AI technologies with big data assistance can aid in the development of crops for climate resilience. Such crops may show higher yields along with enhanced tolerance against different abiotic stresses. With the introduction of innovative technologies such as high-throughput sensors and imaging techniques, field conditions can be examined effectively with high precision. However, in order to assess the efficacy of outcomes, these technologies will undoubtedly necessitate the knowledge and reason of breeders and farmers. Agriculture will rely on next-gen AI approaches in the future to make decisions and suggestions based on big data that are indicative of the environment and system biology-based understanding of plant behaviour.

## 26.11 Genome-Wide Association Study (GWAS) and Association Mapping (AM)

### 26.11.1 Genome-Wide Association Study (GWAS)

The use of biparental populations for QTL mapping has significant drawbacks, such as the lack of restricted allelic diversity. In comparison, the genome-wide association study (GWAS) approach provides many opportunities to investigate the vast allelic variation present in natural germplasm. Without the necessity for linkage group formation, GWAS can yield improved QTL mapping resolution. Due to these benefits, GWAS is being utilized in the breeding of crops such as wheat, maize, oilseed rape, barley, potato, rice, and soybean for the discovery of new genes and alleles, as well as fine mapping of QTLs for abiotic stressors (Deshmukh et al. 2014; Huang and Han 2014; Tian et al. 2011; Huang et al. 2010; Li et al. 2013; Winfield et al. 2016).

#### 26.11.1.1 Rice

GWAS is becoming increasingly popular in rice, thanks to advances in high-throughput sequencing and SNP chip technology. Frouin et al. (2018) and Naveed et al. (2018) discovered 27 and 20 QTLs for salinity tolerance-related characteristics, respectively. For the study of eight salinity tolerance-related phenotypes under stress and non-stress situations, Nayyeripasand et al. (2021) employed almost 33,000 SNP markers. Under salinity stress, 29 genomic areas linked with marker-trait connections were discovered dispersed across 10 chromosomes. On chromosome 1, a genomic area co-located with a known QTL region SalTol1, and on chromosome 2, a potential gene encoding a high affinity K+ transporter (HAK) was discovered.

#### 26.11.1.2 Upland Cotton

Yasir et al. (2019) identified 23 single-nucleotide polymorphisms (SNPs) for stress-related features among 17,264 SNPs observed correlated with salinity stress tolerance in upland cotton. Sun et al. (2019) conducted a genome-wide association study (GWAS) for salt and cold tolerance and published the results in terms of relative germination rate (RGR). A total of 179 polymorphic SSR markers and 11,975 array-derived SNP markers were employed, with RGR-Salt and RGR-Cold being related with 31 and 19 SSR markers, respectively. GhPIP3A, GhSAG29, GhTZF4, and GhTZF4a were classified as candidate genes linked with RGR-Salt out of the 223 genes found in the candidate gene interval. Hou et al. (2018) genotyped 319 upland cotton accessions by 55,060 SNPs for 9 drought tolerance-related traits and reported that 20 quantitative trait nucleotides (QTNs) were distributed on 16 chromosomes which were associated with 6 traits.

#### 26.11.1.3 Wheat

GWAS was used to find SNPs associated with traits for drought tolerance by Ballesta et al. (2020). It was found that 175 SNPs were associated with at least 1 drought tolerance index, whereas 45 SNPs were associated with more than 1 index. Most of the SNPs were found on chromosome 4A, pointing that this chromosome is related to drought tolerance and should be exploited for improvement programmes. Kumar et al. (2012) also found a QTL (QGyp.ksu-4A) on chromosome 4A which was related to grain yield under drought stress.

#### 26.11.1.4 Maize

1229 SNPs were used for genotyping of 350 inbred lines by Bansal et al. (2014), where 3 SNPs were found to be the most important for identifying the drought stress-tolerant cultivars.

### 26.11.2 Association Mapping (AM)

Association mapping (AM) is a different approach to QTL mapping that relies on linkage disequilibrium in a large germplasm collection. AM evaluates the relationship between marker alleles and a given attribute in a natural population, and its accuracy is mostly determined by marker density and mapping populations (Rosyara and Joshi 2012). The process of discovering a single variant within a locus/candidate gene that causes a given trait is referred to as "association mapping". AM benefits from greater genetic diversity and has three key advantages over linkage mapping: higher mapping precision, a greater number of alleles, and a shorter time to establish a marker-trait correlation (Flint-Garcia et al. 2003). AM is a more accurate tool for discovering the genetic basis of complex traits like abiotic stress tolerance (Zhao et al. 2011). AM has been considered as the preferred method for identifying loci involved in the inheritance of complex quantitative traits (Slatkin 2008). Association mapping investigations with sparse SSR and SNP markers in rice have been successful (Qiu et al. 2015; McCouch et al. 2016).

## 26.12 Future Perspectives of Crop Improvement for Stress Combination and Conclusion

There is still a major gap in our limited knowledge about understanding the stress-associated metabolism in combination with the stress tolerance of many plant species. New approaches to developing plants tolerant to a wide range of stresses and stress combinations in crop plants are urgently needed. By deciphering the intricate networks of molecular interactions driving plant acclimatization to field circumstances, studies exploring the response of plants to a mix of diverse stresses could significantly improve our chances of generating crops with enhanced tolerance to field settings. Some progress has already been achieved using genetic engineering technologies in the production of crops that are resistant to a certain abiotic stress situation through genetic alteration of stress-inducible genes, such as gene editing. However, complete understanding of plant responses to combined stress including physiological, biochemical, and molecular responses and unknown stress-responsive pathways helps to create a wide scope for the development of plants to multiple stressors. A better understanding of tolerance will contribute to the understanding of the molecular mechanisms of a gene that contributes to multiple stress that in turn helps to enhance multiple stress tolerance of crop plants.

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# Part V

# Livestock Production and Management

# Understanding Linkages Between Livestock Sensitivity and Climate Variability in Drylands for Developing Appropriate Management Strategies

# 27

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## Abstract

Dryland agriculture is one of the most vulnerable yet significant aspects of farming systems throughout the world. Livestock farming, being one of the prime allied sectors, contributes immensely to the agricultural GVA (gross value added) in drylands. Indian agriculture has witnessed metamorphosis starting from Green Revolution to Operation Flood, and presently, the genomic revolution is paving the way forward for future conjectures. The resilience of Indian dairy sector is reflected in the fact that the milk production in India has increased by 5% to 198.4 million tonnes from 2018–2019 to 2019–2020 and has maintained the top spot in the world despite the adverse effect of COVID-19 pandemic. Apart from all the progress made so far, about 70% of the dairy farmers in the country are still small and marginal, majority of whom are facing the wrath of changing climate and vulnerability, particularly in drylands. Increasing mechanization in agriculture and degradation of grazing lands has further deteriorated the situation, and dryland-adapted livestock breeds have become irrelevant. Against this backdrop, the renewed push for conservation and improvement of indigenous livestock germplasm has instilled new energy to the cause of dryland animal husbandry. Indigenous cattle breeds like Tharparkar, Rathi, Gir and Murrah breed of buffalo are well suited to the harsh climates with good feed-conversion ratio, disease resistance and optimum productivity. Climate-resilient livestock practices, promoting forward and backward linkages

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and public-private partnerships, can lead the dryland revolution in livestock and will strengthen food security in our country.

**Keywords**

Climate change · Livestock practices · Food security

## 27.1 Introduction

Livestock sector acts as backbone for most of small and marginal farmers in the country. India ranks first among the world's milk producing nations since 1998, and during the period from 1950–1951 to 2019–2020, the milk production has increased from 17 million tonnes (MT) to 198.4 MT (BAHS 2020), recording a tremendous growth rate. The dairy sector was one of the most flexible sectors during the COVID-19 pandemic, evident from the fact that world milk production grew by 1.4% in 2020 to about 861 MMT (OECD-FAO Agricultural Outlook 2021–2030 2022), and in India, the world's largest milk producer, production increased by 5% to 198.4 MMT (from 2018–2019 to 2019–2020). Although the rise in the milk production of the country has boosted the dairy sector, the low level of productivity per animal is still a big challenge. The different breeds of livestock well adapted to the different agro-climatic zones of the country provide multiple utility in rural India and are an important aspect of livelihood for marginal farmers of the country.

Dryland agriculture is dominated by monocropping and livestock farming where pastoralists form an integral part depending on mobility for exploiting biodiversity (Davies et al. 2012). Drylands form 68% of country's cultivated area and support 60% of the livestock population (Singh et al. 2004). Low-input system along with seasonal farmer mobility is an important feature of livestock farmers in these regions which subsequently adds to crop diversification in agriculture. Apart from these difficulties of moving continuously in search of new grazing lands, drylands house some of best cattle breeds, namely, Sahiwal, Tharparkar, Gir, Rathi, Kankrej and Red Sindhi which are best milk producers of the country. They act as source of cash flow and a complementary enterprise for making animal husbandry sustainable in these areas.

Livestock farming in drylands is highly multidimensional with small ruminants and poultry complementing cattle and buffaloes during lean periods. Since half of the agriculture income is derived from livestock farming (Shukla and Brahmankar 1999; Birthal et al. 2003), there is a need to highlight key issues and understand the practical challenges that must be addressed, if India is to build the capacities of its rural farming communities to robustly adapt to climate change and to realize the objectives of the National and State Action Plans on Climate Change (NAPCC and SAPCC). Further, promoting more public investments, schemes promoting credit flow at cheap interest rates, special rights for grazing of pastoralist animals and extensive research in drylands can be a game-changer to support the dryland farming community.

## 27.2 Dryland Livestock and Government Schemes

Drylands have different categories depending on the rainfall they receive, viz., dry areas (<750 mm), drylands (>750 mm) and rainfed areas (>1150 mm). The drylands extend from vast arid region of Rajasthan in the north of country along with semi-arid regions of Punjab to arid regions of Madhya Pradesh, Gujarat, Maharashtra, Karnataka, Andhra Pradesh and Tamil Nadu.

Livestock have some special features with regard to their adaptability in these regions irrespective of scarce resources (Davies et al. 2012). Different communities settled in these areas from centuries have also adopted different management practices for sustainability in these areas; one such example is of pastoral community which moves with their animals while utilizing the resources available at their best for earning their livelihood. However, due to socioeconomic changes, pandemics and stringent government acts, their numbers as well as the natural resources available to them are declining day by day. Some of the important government initiatives which have been taken in these areas since independence are presented below in Table 27.1.

## 27.3 Impact of Climate Change on Dryland Livestock

According to the estimates, the average daily temperature has increased by 0.02 °C/year than (Gisnisha Sahu et al. 2021), whereas the average monsoon rainfall has declined by 0.01–1.40 mm/year along with the increasing unpredictability of monsoon rainfalls (www.ASSARadapt.org). Climate change poses a double whammy for the livestock in drylands with enormous consequences by impacting the grassland productivity as well as animal performance. Higher temperatures and lesser rainfall will lead to reduction in the quantity and quality of forages and will also shorten the duration of growing seasons in the dryland ranges. The effects will be manifested in the livestock in the form of lesser intake and reduced feed conversion efficiency (Rowlinson 2008). It will further have a deteriorating effect on animal performance in terms of milk, meat, fibre production and draft purpose and animal health in terms of increased susceptibility to various diseases. The intensity and frequency of extreme weather disasters like droughts, floods, wildfires, dust storms, etc. would also increase. All this will have far-reaching implications for the overall food security, resource use and biodiversity. However, a silver lining is that the effect of climate change would be minimal on livestock breeds which are locally evolved and adapted to the stressors of dryland extensive management systems like extreme temperatures, low precipitation and food and climatic uncertainties (Salem et al. 2011). This is further substantiated with the reports that the economic effect of climate change was severe in intensive livestock farming systems due to huge investments in feed and reduction in milk production. On the other hand, poor farmers practicing extensive farming on community managed lands (as is the case with Indian dryland livestock farming system) were not affected or very less affected (Tui et al. 2021).

**Table 27.1** Summary of livestock development programmes undertaken over the years

| Rural development programmes | Year | Brief description |
|---|---|---|
| Intensive Cattle Development Project (ICDP) | 1964–1965 | ICDP was designed to provide cattle owners with a package of improved practices and envisaged intensive coverage of 1 lakh cows and buffaloes of breedable age for achieving marked impact on milk production. Various input services, viz., propagation of good quality fodder, heath cover, AI service and milk collection centres, were included in the scheme |
| Drought Prone Areas Programme<br>Small Farmers Development Agency<br>Marginal Farmers and Agricultural Labourers Programme | 1970 | It was the first area-specific development programme launched by the government to tackle the special problems faced by those fragile areas, which are constantly affected by severe drought conditions<br>The main aim was to assist the small farmers (2.5–5 acres) who were not benefitted from gains of Green Revolution and to ensure the viability of small farmers<br>It was launched on the recommendations of the report of the All-India Rural Credit Review Committee to assist marginal farmers (land holding <2.5 acres) and agricultural labourers. Those farmers and labourers were selected who were deriving more than 50% of their income from agricultural wages |
| All India Coordinated Research Project (AICRP) on Goat Improvement | 1971 | It was launched in 1971 with the aim to develop new superior genotypes by selective breeding and crossbreeding of indigenous goat breeds with the exotic breeds in order to improve the performance. Initially, the focus was on improvement of milk and fibre production, but in the fifth 5-year plan, the meat component was also added |
| Krishi Vigyan Kendra | 1974 | First KVK was established in 1974 in Pondicherry. There are three fundamental principles of a KVK programme, viz., agricultural production, work experience and priority to weaker sections of society |
| Network Project on Sheep Improvement (NWPSI) | 1990 | Earlier known as All India Coordinated Research Project (AICRP) on sheep improvement, it was converted to NWPSI in 1990. It emphasized on selective breeding and inter se mating in indigenous sheep breeds for improvement in mutton and wool production |
| Employment Assurance Scheme | 1993 | It was started in 1778 blocks located in drought-prone, desert areas, tribal areas and hilly areas of 261 districts. The scheme aimed to provide 100 days of employment for unskilled work to all men and women above 18 years and below 60 years of age, especially the rural poor |

(continued)

**Table 27.1** (continued)

| Rural development programmes | Year | Brief description |
|---|---|---|
| National Livestock Mission (NLM) | 2014–2015 | National Livestock Mission was started with a view to ensure qualitative and quantitative improvement in livestock production systems. Availability of fodder and feed, efforts to prevent animal diseases, conservation and genetic improvement of livestock breeds and capacity building of the stakeholders are some of the important objectives of NLM |
| Rashtriya Gokul Mission (RGM) | 2014 | The major focus of this central scheme has been to undertake the improvement of indigenous breeds and to enhance their productivity. It has been in operation since 2014 and aims to increase the economic prospects of farmers rearing indigenous cattle breeds. Also, the improvement of country-wide non-descript cattle population will be targeted through grading up with elite indigenous breeds like Gir, Sahiwal, Rathi, Red Sindhi, Tharparkar, Kankrej and Hariana |

The detailed impact of climate change on critical livestock variables is described as under:

1. *Soil*: Soil degradation is one of the direct consequences of climate change which will be exacerbated with increasing droughts and flood incidences. Fluctuations in rainfall and overall reduction in precipitation will cause soil salinity which, if goes beyond tolerance limit (>25 dS/m), plant productivity will be highly decreased and overall vegetation will be severely affected. Though carbon sequestration in dryland soil is still a viable alternative in the direction of climate stewardship, the former is a complex interplay involving economic, social and environmental components.
2. *Water*: Livestock water budgeting entails water requirements for drinking, cleaning or bathing and other purposes besides water for fodder growth. Depletion in ground as well as surface water reservoirs may ensue from the fluctuating rainfall patterns and drier climatic conditions due to increased temperature. Furthermore, rising temperatures will witness an additional water requirement for beating heat stress in livestock.
3. *Forages*: Adverse impacts on land and water will seriously hinder the primary productivity of the rangelands and fodder crops. This may pave the way for change in the floral composition of drylands by the substitution of existing vegetation with more hardy and drought-tolerant crops. Additionally, rising temperatures and carbon dioxide levels will favour the growth of fodder shrubs and trees at the expense of herb vegetation, thus changing the faunal composition of the rangeland as well.

4. *Host-Pathogen Interactions*: Changing climate will further push for selection of pathogens and their strains better capable of tolerating the changed abiotic conditions (Morgan and Wall 2009). Accordingly, dynamics of parasites or vectors harbouring those pathogens will also change, as is evident from the wide prevalence of tick spp. in drier regions of Africa. Consequently, sweeping changes would be prevalent in the biomass of the parasite, its preferred hosts and epidemiology of the disease in the rangelands (Salem et al. 2011). Heat stress and feed scarcity will further predispose the animals to the diseases and infestations through lowered immunity levels.

## 27.4 Species: Wise Impact of Climate Change

Climate change is already a threat to the different livestock species dwelling in dryland ecosystems. The gravity of the situation could be gauged from the worsening impact of heat stress seen in different species:

***Cattle*** Heat stress negatively disturbs both the production and reproductive performance in cattle. Higher temperatures activate the heat stress responses in dairy cows, subsequently leading to a 50% drop in milk yield due to a negative energy balance (Baumgard and Rhoads 2013). At a temperature-humidity index (THI) exceeding 76, feed intake as well as milk production falls steeply in dairy cattle (Molee et al. 2011). A decline in milk quality is also reported in higher temperatures due to fall in casein percentage in milk (Bernabucci et al. 2002). Lower sperm concentrations, decreased viability and increased incidences of abnormalities have also been reported in cattle bulls in hotter climates (Soren et al. 2016).

***Buffalo*** Buffalo is one of the most vulnerable animals to heat stress, as is exhibited by the incidence of silent oestrus during the summer season observed in the species. In buffaloes, lactation length is shortened (Upadhyay et al. 2007), calving interval is lengthened (Sastry and Tripathi 1988), oestrous cycle is suppressed and post-partum ovarian activity is hindered (Abayawansa et al. 2011). Shortages in feed availability and deteriorating impact on animal health have been identified as other impediments to buffalo farming in rising temperatures (Escarcha et al. 2018).

***Sheep*** Rising temperatures resulting from changing climate can lead to changes in physiological parameters like rectal temperature, tidal volume and respiration rate and blood parameters in sheep (Lowe et al. 2001; Srikandakumar et al. 2003). Lower feed intake due to heat stress results in slow gain in body weight and, hence, delayed puberty. Decreased libido, lower sperm motility and lesser scrotal volume in rams are further indicative of negative impact of climate change on reproduction (Marai et al. 2008). Besides reproduction, milk production, body growth and wool production parameters are also adversely affected (Sejian et al. 2017).

***Goat*** Goat is considered as an ideal animal model to withstand the adverse effects of climate change owing to its resilient nature suited to tropical dry conditions (Nair et al. 2021). However, high ambient temperatures have been reported to have detrimental effect on overall milk yield as well as its composition including total protein content, casein content, fat content, fatty acid composition and milk coagulation ability (Marino et al. 2016).

***Camel*** Camel, also called as "Ship of the Desert", is accustomed to the arid and semi-arid desert conditions. However, climate change has an indirect effect on camel performance through shrinking grazing lands and frequent droughts. Lack of availability of nutritious grazing resources can cause malnourishment in camel herds. Prolonged drought condition combined with severe water deprivation can reduce milk yield in camel due to dehydration. Another major risk is the transmission of exotic diseases in camels as a result of interaction with other livestock species during water scarcity (Al Jassim and Sejian 2015).

***Horses*** Climate change will hamper the equine husbandry through worsening impact on animal breeding and reproduction and by increasing the susceptibility to various diseases (Summers 2009).

## 27.5 Strategies for Dryland Livestock Development vis-à-vis Changing Climates

Adaptation is the key to develop and sustain dryland livestock farming in the wake of climate change. Adaptation strategies need to be multipronged and directed at different aspects including breeding approach, livestock production and management systems (Rowlinson et al. 2008; USDA 2013). These adaptation strategies need to be tailor-made for different regions as per the location, ecosystem and the prevailing livestock husbandry systems (Rojas-Downing et al. 2017). Finally, climate change mitigation through livestock husbandry should be an integral part of adaptation so as to ensure that farming stays viable and sustainable in drylands. The different approaches have been discussed below:

### 27.5.1 Livestock Breeding

Raising locally adapted livestock breeds is a viable approach to ensure conservation of unique genetic resources as well as to promote economic sustainability of farming (FAO 2010). Dryland breeds, particularly those raised in pastoral or extensive farming systems, have evolved in response to the harsh climatic adversities including high temperatures, water shortages and droughts, etc. and hence may be best bet to survive and thrive in the vagaries of changing climate (Salem et al. 2011). The genetic makeup of these breeds allows them to perform within the constraints of restricted supply of feed and water and with a certain degree of disease resistance.

Consideration of genotype x environment interaction component for animal breeding is indispensable for selecting locally adapted animals. Further, climate-specific traits like tolerance to high temperatures, higher feed conversion efficiency, lower methane emissions, greater disease resistance and others aimed at area-specific issues could be incorporated in the selection indices so as to select climate-friendly and resilient animals (Hoffmann 2010).

Focus should be directed at preparing a detailed breed inventory of the locally adapted breeds with all the relevant and updated knowledge in reference to climate adaptability; maintaining optimum genetic diversity in the breed; and genetic improvement programmes targeting production and adaptability aspects along with in situ and ex situ conservation efforts. These should be supplemented with widespread knowledge sharing among stakeholders regarding the effective management of animal genetic resources (Hoffmann 2010).

Species shift as a result of changes in climate, and the agro-ecosystem is also a possibility as rising temperatures replace the herb vegetation with shrubs and trees. Thus, grazers like cattle and sheep may be replaced with better-adapted browsers like camels and goats as witnessed in Sahel region of Africa (Salem et al. 2011).

### 27.5.2 Livestock Production and Management

Besides animal selection and breeding, modification in livestock husbandry and management systems is a crucial part of climate adaptation. Diversifying livestock herd would act as a check guard against financial instability resulting from extreme climate events like heat waves and droughts (IFAD 2010). In fact, diversification is one of the key strengths of the centuries-old pastoral production systems in drylands (Coppock et al. 1986). Introducing diversification in the crops grown would help in minimizing losses resulting from pest outbreaks and diseases (Batima et al. 2005).

Another novel approach to be adopted for fodder management is the practice of agroforestry. Agroforestry is an integrated land management approach to derive the maximum benefits from a limited land area by planting trees alongside fodder crops and pastures. The role of agroforestry in environmental protection could be highlighted by the fact that planting of nitrogen-fixing trees prevents soil erosion and improves its fertility, wasteland could be utilized meaningfully and appropriate tree-fodder mix variety could be explored (Basu 2014). It will also help in promoting the usage of non-conventional fodder crops in livestock feeding, thus helping in reducing overall costs. An ecological dimension of agroforestry could be highlighted by its role in improving nutrient cycling, maintaining biodiversity and carbon sequestration (Smith et al. 2012). Soil carbon sequestration is a major climate change mitigation strategy and offers the possibility of capturing the atmospheric carbon dioxide and storing it in plant and soil biomass (Nair 2012).

Other adaptation strategies could be rotation of crops and pastures, maintaining the carrying capacity of an ecosystem and changes in timing of management operations in accordance with temperature and rainfall variability (Kurukulasuriya and Rosenthal 2003).

### 27.5.3 Climate Change Mitigation Through Improved Husbandry Practices

Climate-friendly feeding practices like replacement of roughages with concentrates, ensiling of fodder, supplementation of diet with fatty acids, administration of ionophores, etc. can reduce the enteric methane production in ruminants (Salem et al. 2011). Animal dung or manure is considered as an effective fertilizer for crop land and pastures. However, storage of manure for long periods can lead to nitrous oxide emissions, further contributing to greenhouse gases (GHGs). Hence, proper management of manure through short-term duration, anaerobic digestion to produce biogas and covering the stored dung are good ways to reduce the methane emissions arising out of farm yard manure (Gerber et al. 2008; Dickie et al. 2014). Supplementation of dietary tannins also helps to control the GHG emissions.

Carbon sequestration in livestock husbandry could be achieved by discouraging soil tillage, avoiding overgrazing of pasture lands, promoting agro-forestry-based production systems incorporating trees with fodder crops, mixing crops with grass-legume combination, encouraging mulching, introducing soil-friendly organisms like earthworms, etc. (Conant et al. 2001). It has been reported that allowing grazing below the carrying capacity of rangelands can help in sequestering 0.15 gigatons of $CO_2$ equivalent per year (Henderson et al. 2015).

### 27.5.4 Participatory Approach

The indigenous communities and pastoralists raising the livestock house a treasure of knowledge regarding their animal genetic resources and the ecosystems. Therefore, adaptation strategies should be prepared by exhaustive deliberations with all the stakeholders involved including the former. A detailed roadmap for the better management of dryland resources could involve analysis of the risks involved, disaster mitigation and preparedness and short-term and long-term adaptation strategies. Accordingly, research and development initiatives need to be devised on similar lines, and participatory technology development should be encouraged while appreciating the indigenous traditional knowledge. Awareness and incentive programme would be a critical element in the sustainable management of drylands.

## 27.6 Conclusions

Climate change vis-à-vis livestock production in drylands is a feedback loop where livestock could be visualized as being a part of the problem as well as the solution. Being a critical source of economic sustainability for millions, dryland livestock farming is accustomed to the weather brutalities and extremes. However, climate change threatens to severely dent the livestock production systems in drylands by restricting feed and water resources, hindering animal performance and deteriorating animal health. An integrated approach to bring resilience in dryland livestock farming along with climate change mitigation can address this huge challenge. Adaptation strategies may include bringing diversification in species and breed composition, selecting locally adapted breeds, agroforestry practices, climate change mitigation through soil carbon sequestration, reduction in enteric methane fermentation and manure management. However, local as well as global efforts would be coherent and complimented if the roadmap prepared and action executed is in a participatory mode involving all the stakeholders.

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# Grass-Legume Intercropping for Enhancing Quality Fodder Production in Drylands

# 28

P. S. Renjith, Sheetal K. Radhakrishnan, and Abhishek Patel

## Abstract

Livestock sector, accounting for 4.2% of national gross domestic product plays a significant role in the socio-economic development of rural economy, notably of dryland regions where adverse extreme climatic conditions prevail. In dryland regions, poor nutrition owing to wide gap in demand and availability of fodder and feed resources is identified as one of the major reasons of low livestock productivity. The poor quality of available fodder from the prevailing fodder production systems further aggregates the situation and necessitates enhancement of quality fodder production. Intercropping of grass and legumes is an important, low-input production strategy for the development of sustainable fodder production systems, especially in fragile arid zones, owing to its multiple benefits over monocultures of either grasses or legumes. The grass-legume intercropping provides an opportunity to develop sustainable production systems with higher productivity and profitability; improve soil fertility through biological nitrogen fixation; minimise the adverse impact of moisture and nutrient stress; reduce yield loss caused by weeds, diseases, and pests; and improve the protein content and quality of the overall livestock diets. It is imperative to ensure that there will be minimum competition between component crops for space, light, nutrients, and water for making a successful grass-legume intercropping system. The success of such systems largely depends on choice of crops, their differentiating growth, development, stature, root behaviour and maturity, crop density, and time of planting. The constrains that hinder the adoption of grass-legume intercropping systems, such as availability of efficient strains of *Rhizobium*, high-quality seeds,

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lack of awareness about the importance of legumes and their inclusion in fodder production systems, and technical know-how of complex intercropping systems, must be addressed effectively to popularise it among resource-poor and marginal farming community for enhancing the quantity and quality of fodder in drylands.

**Keywords**

Drylands · Fodder quality · Grass-legume intercropping · Livestock sector

## 28.1 Introduction

Drylands form about 41% of Earth's land area and are of vital significance as they are inhibited by nearly one-third of the global population (Singh et al. 2018; Feng et al. 2020). High levels of poverty are prevalent among inhabitants of drylands, and nearly half of the inhabitants depend on ecosystem services of drylands for their livelihoods and well-being (White et al. 2002; Thomas 2008). Drylands are characterised by a scarcity of water; low, erratic, and variable precipitation; low fertile soils, which are vulnerable to wind and water erosion and are subject to intensive mineral weathering; and the incidence of extreme events like droughts and heat waves, which all adversely affect both the natural and managed ecosystems and limit the production of crops as well as livestock, fodder, forage, woody, and other plants and result in relatively very low and markedly unpredictable yields of crops and livestock production. Drylands are defined by the aridity index (AI), which is expressed as the ratio between average annual precipitation and potential evapotranspiration. Lands with an AI of less than 0.65 are classified as drylands, which are further subdivided into hyper-arid lands, arid lands, semiarid lands, and dry subhumid lands (Middleton and Thomas 1997).

The livestock sector, accounting for 4.2% of the national gross domestic product, plays a significant role in the socio-economic development of rural economies, notably in dryland regions where adverse and extreme climatic conditions prevail. Milk production provides employment and livelihood to almost 70 million rural households, the majority of whom are landless or small and marginal farmers (DAHD 2018). Dairying provides a source of income for millions of disadvantaged families while also supplementing their protein and nutrient intake requirements, thereby contributing immensely to the country's food security needs.

The average milk and meat yield of Indian animals is lower than the global average. In dryland regions, poor nutrition owing to the wide gap in demand and availability of fodder and feed resources is identified as one of the major reasons for poor livestock productivity. Normally, the animals are fed with low-quality (in terms of protein, minerals, and available energy) naturally grown grasses, shrubs, and weeds in the agricultural lands, and no standard practice of forage or fodder production is followed. The livestock sector, thus, faces a big challenge in terms of the quantity and quality of forage and fodder crops. The cost of feed alone constitutes around 60% of the cost of milk production as farmers primarily rely on concentrate animal meals to get higher milk yields (Halli et al. 2018). Presently, the country faces a net deficit of 35.6% green fodder, 11% dry crop residues, and 44% concentrated feed ingredients which makes livestock rearing more challenging (IGFRI 2015). Green forage or fodder that is high in proteins, minerals, vitamins, carbohydrates, and micronutrients, as well as high dry matter intake, digestibility, and low fibre content, could help reduce livestock feeding costs and boost animal productivity.

## 28.2 The Concept of Intercropping and Its Mechanisms

Intercropping is the agronomic practice of growing two or more crops simultaneously on the same field during a growing season (Willey 1979) but without necessarily sowing or harvesting at the same time (Vandermeer 1989; Malézieux et al. 2009). It is a globally practised key low-input production strategy in low-input cropping systems. The basic rationale behind all the intercropping practices is the assumption that some benefits, such as biological diversity, co-operation, symbiotic association, and stability, could be achieved from mixing crops as compared to sole cropping due to differences in the ways species exploit or act in relation to the environment in which they are grown. Thus, intercropping could be employed as an excellent strategy for the design and development of sustainable fodder production systems, especially in fragile dryland areas, owing to its manifold benefits over monocultures of either grasses or legumes.

Intercropping is based on the ecological principles of competition, complementarity, and facilitation, and a good balance among them determines the success of intercropping. It aims to produce a greater yield on a given unit area by making use of resources or ecological processes that would otherwise not be utilised by a single crop. Resource partitioning and facilitation contribute to complementarity among crops under intercropping systems. Differences in resource acquisition traits cause resource partition or niche differentiation, leading to enhanced utilisation of available resources by component crops. Crops that differ from each other in traits such as rooting depth, phenology, and vegetative architecture can be grown in an intercropping system that can minimise competition and increase resource partitioning. A classic example is the intercropping of maize and legumes, in which resource partitioning is driven by differences in traits among the nitrogen-fixing legumes that cover the soil and suppress weeds and the tall maize that captures light from heights well above the legumes.

The process by which one crop species provides or facilitates a limiting resource or improves the environmental condition for the companion crop species is referred to as facilitation. Processes such as crop species with deep taproot supplying water to companion species by hydraulic lift, legumes providing biologically fixed nitrogen to grasses, beneficial changes in the rhizosphere due to intercropping, etc. come under facilitation.

## 28.2.1 Types of Intercropping

### 28.2.1.1 Mixed Intercropping

When two or more crops are grown simultaneously without any distant row arrangement for each of the crops, it is termed “mixed intercropping”. Also, when crops are raised in rows with a mix of crops within the row, it is still counted as mixed intercropping (Ofori and Stem 1987). It is most common in subsistence food production systems where yields are uncertain and field operations are mostly done manually.

### 28.2.1.2 Row Intercropping

It is the raising of two or more crops simultaneously in the same field with definite rows (Andrews and Kassam 1976). It is a common practice adopted in intensive agriculture targeting optimisation of productivity and use of resources.

### 28.2.1.3 Strip Intercropping

Strip intercropping is a form of intercropping that is mostly adopted in highly mechanised agricultural production systems in which raising of two or more crops is done simultaneously in strips wide enough to allow cultivation of each crop separately but narrow enough to cause adjacent crops to interact agronomically (Andrews and Kassam 1976). The strips are often rotated annually, and the width of the strips is critical to the structure and function of strip intercropping. The combination of erosion permitting and resisting crops grown in alternate strips running perpendicular to the slope of the land or the direction of prevailing winds is known to reduce soil erosion and achieve yield stability.

### 28.2.1.4 Relay Cropping

Relay cropping describes an agronomic practice in which the life cycle of one crop overlaps that of another crop. There must be some overlap in the life cycles of the two crops, and usually a second crop is sown soon after the first crop has reached its reproductive stage of growth but before it is ready for harvest (Andrews and Kassam 1976). It helps to intensify agriculture by enabling double cropping in regions with a limitation of soil moisture and where the sowing window is too short to allow two discrete sequential crops. It can also help to efficiently utilise time, labour, and equipment. However, the succeeding crop in relay cropping yields less compared to normal sowing in sequential cropping.

Based on the percent of plant population maintained for each crop in the intercropping system, it is divided into the following two categories.

(a) Additive Series

In this system of intercropping, one crop is sown and maintained at its optimum sole crop population, known as the base crop. Another crop known as intercrop is introduced into the base crop by sowing within the row spaces of the base crop, or sometimes the planting geometry of the base crop is tweaked to accommodate the intercrop. The population of the intercrop is maintained at less than its recommended population in sole cropping. Land equivalent ratio is greater in the additive series than in the replacement series and is considered more efficient than the latter.

(b) Replacement Series

In this system of intercropping, all the crops involved are called component crops, and the plant population of the component crops is maintained at less than their recommended population in pure stand. A certain proportion of the population of one component crop is sacrificed, and the component crop is introduced in that place. In the replacement series, competition among species is relatively less than in the additive series.

### 28.2.2 Crop Combinations in Intercropping

As the success of intercropping systems greatly depends on the interactions between the component species, available management practices, and environmental conditions, choosing an appropriate intercropping system can be quite challenging. The component crops of an intercropping system must be carefully chosen, taking into account the local environment as well as the available crops and their varieties. It is crucial that the component crops do not compete with one another for resources like nutrients, water, sunlight, or physical space. Component crops are determined by the length of the growing season and how well the crops have adapted to particular environments. Crops of different root architecture, canopy structure, height, nutrient, and light requirements in intercropping systems could cause complementary utilisation of available resources and greater yield per unit area.

### 28.2.3 The Need for Intercropping of Grasses and Legumes

The poor quality of available fodder from the prevailing fodder production systems where naturally grown grasses, shrubs, and weeds are fed and no standard practice of forage or fodder production is normally followed necessitates the enhancement of quality fodder production. Grasses, especially cereals, are widely used in livestock nutrition due to their potential to produce high dry matter and thereby supply a large amount of energy for animals at a low cost. However, grasses often contain very low protein and thus have low fodder quality and nutritive value. Although protein supplementation of low-quality forage increases animal performance, doing so could be quite expensive and could act as one of the biggest economic drains on livestock production. Legumes, with their high protein content, could be used in livestock nutrition and increase fodder quality to an acceptable level at a low cost compared to alternative options. As legumes have low dry matter yield, sole cropping of them for forage production is not viable; an acceptable balance of forage yield and quality could be achieved by adopting intercropping of grasses and legumes compared to respective sole cultivation.

Poor quality and quantity of forage during the dry season leads to poor growth of animals, poor reproductive performance, low resistance to insects and pests, and eventual poor yield. Grass-legume intercropping could possibly act as a solution to the prevailing acute shortage of forage for livestock in dryland areas, especially during the dry season. An acceptable balance of forage yield and quality could be achieved by intercropping of grasses and legumes, which normally have high biomass producing potential and are good sources of high carbohydrate and protein, respectively. Intercropping improves forage quality compared with monoculture of grasses and produces more dry matter compared with sole cropping of legumes. The majority of the successful intercropping systems grown globally consists of grass/cereal-legume intercrops.

## 28.3 Advantages of Grass-Legume Intercropping

### 28.3.1 Yield Advantage

Intercropping can facilitate more efficient utilisation of the available resources and provide increased productivity compared to that of each sole crop in the mixture. Sometimes, even when the overall yield level remains the same, the advantages of intercropping can be manifested as increase in monetary units or nutritional values. Available growth resources are intercepted, utilised, and transformed into crop biomass more efficiently over time and space due to differences in the competitive ability of component crops, asynchrony in resource demand, and variations in growth characteristics such as rate of canopy development, rooting pattern, and depth, adaptation of canopies to irradiance levels, and final canopy size. Yield is the basic factor for evaluating benefits of intercropping, and land equivalent ratio (LER) is the most common index used to measure productivity of intercropping systems. It is the summation of ratios of the yield of each companion crops involved in intercropping system to its corresponding pure stand yield. There have been multiple studies which suggest greater yield advantage due to intercropping in low-nitrogen availability systems. The intercropping of grasses (*Cenchrus ciliaris*, *Cenchrus setigerus*, *Dichanthium annulatum*, and *Sporobolus marginatus*) and two legumes (*Clitoriaternatia* and *Stylosanthes hamata*) as strip intercropping in 2:1 ratio recorded higher crude protein yield and dry matter yield compared to its sole counterpart from the same area with similar level of management at Bhuj, India (Kumar and Machiwal 2017). Compared to maize grown alone, intercropping of the former with cowpea has been shown to increase light interception per unit area, decrease water evaporation, and improve soil moisture conservation (Ghanbari et al. 2010).

### 28.3.2 Fodder Quality

In arid and semiarid environments, where the resources are limited, the grass-legume intercropping can be a suitable strategy to increase good quality fodder production without adding extra burden on resource poor farmers (Sadeghpour et al. 2013). Quality of dry matter production per unit area is more balanced in grass-legume intercropping, and multiple studies indicate that intercropping improves the quality of produce and, in particular, its protein concentration compared with sole cropping of cereals in low-nitrogen availability systems (Gooding et al. 2007; Naudin et al. 2010). Intercropping with legumes provides more availability of nitrogen during the growth stages of cereals in nitrogen-limiting systems, thereby improving their growth and eventual increase in grain and biological yield as well as protein content in the grains.

### 28.3.3 Suppresses Weeds

Legumes generally are known to be weak competitors against weeds, and weed infestations severely limit legume growth and yield. Intercropping of legumes with grasses facilitates dominance in competition over weeds irrespective of the crop species used and reduces weed. Intercropped grass is a critical component in enhancing the competitiveness of legumes towards weeds and helps to reduce weed biomass, which in turn means fewer requirements for weed management practices. Moreover, the combination of more erect leaves of grasses with more horizontal spread of legumes thwarts the competition of weeds.

### 28.3.4 Improved Use of Resources

The intercropping technique makes better use of the resources that are already available, such as the amount of land, soil moisture, soil nutrients, sunlight, and carbon dioxide which is reflected in higher production of biomass. It can be said that the crop species chosen must have higher complementarity and less intraspecific competition in order to make better use of available resources, for example, when different component crops have interspecific complementarities among themselves, such as differences in shoot architecture and crop duration, which facilitate a more dynamic occupation of space and an increase in the interception of light and consequently higher biomass and yield.

## 28.4 Limitations of Grass-Legume Intercropping

There are some limitations of intercropping also observed over monocropping. The difficulty in practical management of critical agronomic operations is a major drawback of intercropping, especially where farm machinery is adopted or when the component crops cultivated in intercropping have different requirements of nutrients, water, and plant protection. As farm machinery used for different farming operations are made for big uniform fields, adoption of farm mechanisation is really difficult in intercropped fields. Selection of intercrops is highly important in intercropping systems, and if the choice of crop species is not appropriate, interspecific competition and allelochemicals can cause adverse effect in the productivity of crop mixture.

## 28.5 Conclusion

For the dryland areas, wherein agriculture systems are livestock-centric and livestock remains the primary source of livelihood for the inhabitants, enhanced production of quality fodder is an essential requirement. The grass-legume intercropping systems can be employed as a sustainable management strategy to ensure stable to higher fodder productivity, improve fodder quality, and help in soil conservation, weed management, and restoration of soil health in dryland areas for the overall development of the livestock sector. Therefore, it is necessary to develop location-specific, highly productive, and financially rewarding intercropping systems across various dryland zones and to upscale the same.

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# Part VI

# Improving Livelihood and Socio-Economic Status of Dryland Farmers

# Economic Analysis of Sustainable Dryland Agriculture Practices

# 29

Barre Jyothsna Priyadarshini and Durgam Sridhar

## Abstract

Sustainable food production is the greatest challenge of the twenty-first century due to declining soil fertility status and increasing climatic stresses. Around 40% of the world's geographical area is covered by arid and semiarid regions, which are the habitat of over 700 million people. Developing countries account for over 60% of these drylands. In the years ahead, these dryland areas will continue to produce the majority of the world's food grains to sustain the rising population. In comparison to the humid and subhumid zones, however, yields are extremely low. Agricultural sustainability indices have been created in the absence of climate variability here so far. Rainfall has such a large impact on agricultural performance, particularly in dry farming, that it cannot be overlooked when evaluating sustainability. This chapter addresses India's dryland farming areas, its climate, cropping patterns, and economic and social considerations, and there is a need for research and climate-resilient agriculture strategies and technologies. Climate change has an impact on agriculture in both direct and indirect sustainable food production, and it is the greatest challenge of the twenty-first century due to declining soil fertility status and increasing climatic stresses. Around 40% of the world's geography affects crops, soils, livestock, and pests. Climate change has a direct and indirect impact on agriculture, influencing crops, soils, livestock, and pests. Creating a heat- and salinity-resistant cultivars, as well as flood- and drought-resistant cultivars; modifying existing cultivar's crop management

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practices; improving water management; adopting new farm techniques such as resource-conserving technologies (RCTs) and crop diversification; improving pest management, better weather forecasts, and crop insurance; and leveraging farmers' indigenous technical knowledge have all been potential adaptation strategies. It is necessary to develop a policy framework for implementing adaptation and mitigation methods in order for farmers to be protected from the harmful effects of climate change, as well as the country's food and nutritional security. A well-designed economic analysis would help deliver the solution of dryland agriculture technology across the whole world in a similar manner.

**Keywords**

Food production · Climatic stress · Population · Dry farming · Climate-resilient agriculture · Crop diversification · Pest management · Mitigation · Nutritional security · Resource-conserving technology · Food insecurity

## 29.1 Introduction

Sustainable food production is the greatest challenge of the twenty-first century due to declining soil fertility status and increasing climatic stresses. Around 40% of the world's geographical area is covered by arid and semiarid regions, which are the habitat of over 700 million people. The majority of the world's food grains are made up of around 60% of these, which are required to sustain the world's rapidly rising population. However, when contrasted, drylands are found in developing countries. In the years ahead, these dryland areas will continue to produce in the humid and subhumid regions, and yields are extremely low. To this point, agricultural sustainability indices have been developed in the absence of climate variability. Agricultural subsidies help farms to be more economically and socially sustainable. Those linked to agro-environmental programmes, on the other hand, are the only ones that are truly useful in improving all three aspects of agricultural sustainability, insofar as, in addition to their effects on private profitability, they also produce clear environmental benefits as a result of such programmes' environmental demands (Atance and Barreiro 2006). Rainfall has a huge impact on agricultural productivity, especially in dry farming. When assessing sustainability, it cannot be disregarded. Climate change affects agriculture in both direct and indirect ways, affecting crops, soils, livestock, and pests. Climate change management necessitated the development and broad acceptance of climate change mitigation and adaptation technology among farmers. Developing heat- and salinity-resistant cultivars, as well as flood- and drought-resistant cultivars; changing crop management, crop diversification, and pest management; implementing innovative farm techniques such as resource-conserving technologies (RCTs), crop diversity, and pest management, as well as better water management method as a possible adaptation method; improving water management practices; and applying innovative farm strategies such as resource-conserving technologies, weather forecasts, crop insurance, and harnessing farmers' indigenous technical experience have been recommended.

To safeguard farmers from the harmful effects of climate change and to preserve the country's food and nutritional security, a policy framework must be designed in order to adopt adaptation and mitigation techniques. Land degradation is exacerbated by climate change, food scarcity, and biodiversity loss. Furthermore, present trends in dryland degradation are affecting the efficacy and long-term viability of restoration initiatives. These reasons highlight the necessity of preserving healthy drylands around the world, as well as planning for a more resilient global future. Dryland ecosystems (arid and semiarid) cover more than 3 billion ha and are home to 2.5 billion people; it is a place of residence for almost a third of the world's population and occupies 41% of the world's land area. Due to their vastness and current considerable uses, drylands and their accompanying agricultural production systems are immensely important. Dryland ecosystems, for example, produce roughly 40% of total food grain output and maintain two-thirds of India's cattle herd, according to the study (CRIDA 2011).

Natural resource scarcity has resulted in persistent overexploitation—and, as a result, land degradation—in many dryland ecosystems. In South Asia alone, about 46.5 million ha of land is defined as degraded, and thus production systems' sustainability has become a major area of concern. The majority of agricultural production system sustainability assessments are comprehensive and on a large scale and often described by a single indicator. At the farming and farm system scales, there have been few attempts to develop composite sustainability indices using multiple indicators. Existing studies almost always focus solely on economic or environmental outcomes or employ specific indicators like nutrient balance or water productivity (e.g. Haileslassie et al. 2011; Rego et al. 2003). In the study area, farm typologies are generally based on the size of the holdings (e.g. Haileslassie et al. 2013a, b), such as marginal (1 ha), small (1–2 ha), semi-medium (2–4 ha), medium (4–10 ha), and big (>10 ha) holdings. The current study examined two hypotheses. First, within dryland farming systems, there are many different farm systems, each with its own livelihood asset and agricultural practices. Despite typologies based on land holding size, types based on fundamental livelihood assets could assist in evaluating the opportunities and restrictions of farm technology adoption (Giller 2013; Riveiro et al. 2013; Jain et al. 2009). Second, agricultural sustainability varies by farm typology, which establishes relative reference values for assessing sustainability at different spatial, temporal, and social scales. To put it another way, sustainable development is increasingly viewed as a dynamic process. So, in the absence of clear-cut targets, it is rather common to conduct a relative sustainability assessment of a range of development scenarios. This also permits future development tendencies to be captured instead of just evaluating the current scenario. In this regard, Van Cauwenbergh et al. (2007) demonstrate that reference values are an important component of sustainability evaluation and argue that reference values provide users with advice in the system of continuous improvement toward sustainability.

They considered determining sustainability by comparing an indicator value to a previously set absolute reference or by comparing indicator values from multiple systems to one another. Absolute reference values are used to compare sectors, farm typologies, farming systems, and commodities, whereas relative reference values are used to compare sectors, farm typologies, farming systems, and commodities. Floridi et al. (2011) claim that scientific knowledge can also be used to identify indicator (s) and determine sustainable ranges for them. However, in many other circumstances, we lack accurate objective reference points, leaving benchmarking against actual performance as the sole alternative. Relative composite indices, in this example, enable comparison across countries, regions, and time: they depict relative sustainability. A comprehensive dryland research programme has been developed by the Indian Council of Agricultural Research (ICAR). The All India Coordinated Research Project for Dryland Agriculture (AICRPDA) was founded in 1970 in Hyderabad, Andhra Pradesh, by the Indian Council of Agricultural Research (ICAR) and the Canadian International Development Agency (CIDA). The preamble was Better Crop with Every Rain Drop.

## 29.2 Dryland Farming Techniques

Dryland farming is the profitable production of crops, without irrigation, of land with a low average or highly variable rainfall (Cresell and Martin 1998).

### 29.2.1 Increase Water Absorption

Prevent the formation of a crust on the soil's surface. The tendency for soils to pool at the surface and form a barrier or crust against water intake is probably the greatest impediment to a high rate of water absorption.

### 29.2.2 Reduce the Run-Off of Water

To the extent that water logging is not a problem, the run-off of water and its attendant erosion must be stopped.

### 29.2.3 Reducing Soil Evaporation

Each grain is surrounded by a continuous film of water in the soil. Water is pushed up from below to replenish evaporated water near the surface, thinning the film. Wilting occurs when the soil gets too thin for plant roots to absorb.

### 29.2.4 Reducing Transpiration

All growing plants extract water from the soil and evaporate it from their leaves and stems in a process known as transpiration.

## 29.3 Agricultural Economists Can Improve the Quality and Comprehensiveness of Agricultural Systems Research in Six Areas

- Conducing a comprehensive budgeting and investment analysis of alternative technologies and systems
- Incorporating whole-farm factors and institutional realities into system evaluations
- Taking into account the overall pricing effects of new technologies or policies
- Adding risk considerations to the analysis
- Considering aggregate price effects of new technologies or policies
- Taking into account the effects of technological or policy changes on the overall welfare of society
- Estimating economic values of environmental and other non-market effects

## 29.4 Budgeting and Investment Analysis

Agricultural scientists and farmers are typically motivated to assess the benefits, costs, and profitability of new technology or production methods that appear promising. To ensure that results are comparable from study to study and region to region, standard cost accounting procedures must be used; unfortunately, different accounting systems are occasionally used by researchers, making it hard to compare the findings of different studies unless the original economic and production data are accessible.

Non-monetary costs, such as unpaid family labour or the cost of a farm-grown shed, are referred to as opportunity costs by economists. These products are evaluated at their next best use if there is one. For example, the cost of family labour would be the wage that would be received for that labour in alternative employment. When comparisons are made, the cost of a certain input, such as labour, should typically be included for all options even though labour may be a cash cost for one option and an opportunity cost for the other. An exception would occur if the decision-maker explicitly desires to use “returns over cash costs” as the profit measure to be maximized. “Fixed costs of assets” such as machinery and land are costs that do not vary with the level of production. In contrast, variable costs such as fuel, labour, seed, and livestock feed vary directly with the amount of land or livestock in production. Fixed or investment costs for machinery include depreciation, interest (actual and opportunity), taxes, housing, and insurance.

In the dryland system, livelihood diversification does not always imply sustainability. Despite the widespread belief that diversity of farm livelihoods benefits risk spreading, consumption smoothing, labour allocation smoothing, credit market failures, and dealing with certain types of shocks, diversification may result in stagnation on the home farm (Ellis 2000). This usually happens when distant labour markets for male labour are buoyant, resulting in a shortage of the labour force needed to meet peak farm production demands like land preparation and harvesting. Furthermore, when living in a rainfed environment, households strive to reduce danger. Diversifying economic activities; investing in low-external-input, low-capital investment technology, and investing in social contacts to maintain a social safety network are all risk avoidance measures. Low-risk livelihood methods are inevitably low-returning. Migration to urban centres for labour work is a common type of income diversification strategy in the research area, which supports (Ellis 2000) ideas and likely explains the negative and strong association between the economic sustainability pillar and livelihood diversification.

## 29.5 Methodology

The multidimensional conception of SDA requires the SLSI to be a composite of three indices, namely, the Ecological Security Index (ESI), Economic Efficiency Index (EEI), and Social Equity Index (SEI), in order to account for both conflicts and synergies among SDA's ecological, economic, and equity components in a realistic context (SEI).

Then, we have:

$$\mathrm{SLSI}_{ijk} = X_{IJK} - \min K \frac{X_{IJK}}{\max} K - \min K\, X_{IJK} \tag{29.1}$$

$$\mathrm{SLSI}_{ijk} = \max k\, X_{IJK} - \frac{X_{IJK}}{\max} K - \min K\, X_{IJK} \tag{29.2}$$

where

$i$ = Variables (1, 2, 3, . . ., $I$)
$j$ = Components (1, 2, 3, . . ., $J$)
$k$ = Districts (1, 2, 3, . . ., $K$)

Equation (29.1) pertains to factors that have a positive impact on SLS, while Eq. (29.2) applies to variables that have a negative impact on SLS. The numerators in Eq. (29.1) denote the amount to which the $k$th district outperformed the region (s) with the weakest performance in the $i$th variable representing the $j$th component of its SLSI. The denominator is actually the range, i.e. the difference between a variable's highest and minimum values across districts, which is a simple statistical measure of the variable's total variance. The denominator, in fact, serves as a scale or measuring rod by which the performance of each region is evaluated for a given variable. Scientific criteria, social norms, or even policy objectives might be used to identify exogenous scales. The indices for individual components of SLSI were calculated as a simple mean of the indices of their respective variables once the $\mathrm{SLSI}_{ijk}$ for all variables was determined.

$$\mathrm{SLSI}_{jk} = \sum_{i=1} \mathrm{SLSI}_{IJK} I/I \tag{29.3}$$

where

$j = 1, 2, 3, \ldots, J$
$k = 1, 2, 3, \ldots, K$

The composite indicator was built for each region as a weighted mean of the component indices generated from Eq. (29.3), i.e. $W_{jk}$ in Eq. (29.3) defines the weight allotted to the $j$th component of the SLSI of the $k$th area, with the constraint $W_{ik} + \ldots + W_{jk} = 1$. If the weights are equal and sum up to one, SLSI is calculated as a simple mean. When the weights differ across all $j$s and $k$s, SLSI is calculated as a weighted mean. If the weights are identical and sum up to unity, then SLSI is calculated as a simple mean. SLSI is calculated as a weighted mean when the weights are different across all $j$s and $k$s. The former is abbreviated as “SLSI”, whereas the latter is abbreviated as “SLSI*”. Saleth and Swaminathan (1993) established that PQLI, HDI, and SLSI are among the most extensively used composite indices today, although they are based on an unrealistic assumption of equal weights, owing to the lack of an appropriate technique for determining the weights. By developing a weighted scheme with specified desirable properties, this section gives a simple and generalizable method for building a more realistic weighted composite index. Because the SLSI is composite in nature, and the relative importance of its components changes across districts, it is necessary to develop a weighting system. While a more sophisticated approach that derives weights using some form of social welfare function or econometric approaches such as factor analysis, for example, is a possibility, both the conceptual and data-related issues limit their practical utility and applicability. “Delphi” approach, in which the weighting scheme is based on the learned judgement and opinion of a panel of experts and scientists, is similar. A linear programming framework was used to design the weighting method in this case. The weighing scheme was created with the following two desirable characteristics in mind: It assigns varying weights to different SLSI components as well as across districts for every particular component. It was necessary because the scheme’s weightage assigned to different components of the composite indicator should be inversed to their relative significance as reflected by their values, and (1) the relative significance of components and variables representing them varied across districts, and (2) the scheme’s weightage assigned to different components of the composite indicator should be inversed to their relative significance as reflected by their values. The many components of SLSI highlighted the practical reason and requirement for the equalizing condition indicated by the second characteristic. The second feature, a weighted SLSI, helps in resolving and mitigating such a disparity issue. The approach used to produce the weighting scheme with the aforementioned two features in a more generalized version is as follows:

$$\text{Max} \sum_{j=1}^{j} a_{jk} X_{jk}$$

Subjected to

$$\text{Max} \sum_{j=1}^{j} a_{jk} = 1$$

where

$a_{jk}$ = Coefficient associated with the $j$th component of SLSI of district $k$
$X_{jk}$ = Value of the $j$th component of SLSI of district $k$

In other words, the problem specified above states that the weighted sum of the value components of SLSI is maximized such that the sum of the weights is up to unity. Due to the very nature of the maximization problem specified above, its solution, i.e. $a_{jk}$ ($j = 1, 2, 3, \ldots, J$), will be greater than others, and those $X_{jk}$ ($j = 1, 2, 3, \ldots, J$) that have higher values than others and vice versa. It requires instead the $a_{jk}$ ($j = 1, 2, 3, \ldots, J$) to assign higher weights to those $X_{jk}$ ($j = 1, 2, 3, \ldots, J$) that have lower values and vice versa. This is for two important reasons. First, using the $a_{jk}$ as weights could result in a skewed composite indicator that exaggerates the impact of a higher-performing component while underestimating the contribution of the lowest-performing one, contradicting the aim of the weighting method. This could influence policy-making since it may be required to pay more attention to underperforming components. Second, because this is a cross-sectional comparison at a certain point in time, we must take into account the variable levels of emphasis that different districts place on specific SLSI components. To obtain $a_{jk}$ that will assign a higher weight to $X_{jk}$ that has a lower value, we first take the inverse of $a_{jk}$, i.e. $1/a_{jk}$, and denote this ratio as $r_{jk}$; then the actual weight to be assigned to $X_{jk}$, i.e. $W_{jk}$, will be equal to ($r_{jk}$). By repeating the procedure, we could find a set of the district- and component-specific weights for the districts for which the SLSI was to be constructed. The following is a summary of the weighing procedure: To begin, get the inverse of the proportional contributions of ESI, EEI, and SEI to SLSI. The ratio of each component's inverse contribution to the sum of all three inverse proportions will then be used to assign weights to each component.

## 29.6 Conclusions

Agriculture reforms should be initiated as a war effort, drawing together as many resources as possible and revolutionizing agriculture. Agriculture reforms should be fought like a war, bringing together all available resources and transforming agriculture into a well-organized organization that best benefits farmers. The key to the second green revolution and India's much-desired evergreen revolution should be to turn agriculture into a structured business with the farmer as the entrepreneur. Farming should be taken up with the motive of profit-making rather than just making a subsistence living. With huge diversity in the number and variety of crops that we produce, variations in agro-climatic conditions, soil type, and prevailing inequalities in the state growth levels, it is critical to carry out the plans through small-scale efforts and adequate coordination among all stakeholders. These issues need to be considered to meet the targets laid out in the Eleventh Plan strategy to raise agricultural output. Therefore, the prevailing policy instruments need to be relooked at, redefined, rewritten, and efficiently implemented to take care of dryland farming. There is a need to encourage more private investment in agriculture, and incentives such as tax deductions or perks could be provided. There is also a strong need for private-public partnership, not only to start new projects but also to support and maintain the existing public structure.

## 29.7 Recommendations

Large numbers of farming households must be encouraged to continue sustainability indicators and adopt coordinated resource management in order for dryland sustainability to be achieved. Sustainability indicators are indicators that can be used to show and track dryland sector conditions and development. According to the results, farmers should be taught about using water conservation, using conservation tillage, using Integrated Pest Management, and farm control for pests and weeds. Extension training courses could be useful to teach wheat farmers in this regard. In recent years, an increasing number of studies have shown that participation by local people is one of the vital components of success in sustainable agriculture. These approaches represent an opportunity to increase learning from farmers. Farmers are the world's largest users and managers of land, water, and other natural resources. The majority of these men, women, and young farmers will require meaningful knowledge, appropriate equipment, and solid technical guidance not only to raise their agricultural output and income but also to ensure that farming and rural life are more sustainable. For example, to have a successful sustainable program such as an IPM program or nutrient management program, society needs to invest in ecological and pedagogical studies that can be transferred to farmers.

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# Adoption of Sustainable Dryland Technologies for Improving Livelihood of Farmers in Developing Countries

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## Abstract

Drylands are home to an estimated two billion people across the world, about 90% of who live in developing countries. Drylands represented 43.2% of total global area in 2020 and are predicted to be 44.2% in 2050. Human population in drylands is fret with poverty, food insecurity, biodiversity loss, frequent droughts, environmental degradation and water scarcity at critical times during agricultural seasons which are aggravated by climate change. In drylands, agriculture depends upon the erratic weather conditions and is referred to as dryland farming. Dryland farming is the cultivation of crops without irrigation in regions of limited moisture, receiving typically less than 500 mm precipitation annually. Sustainable technologies and risk management strategies are required to be adopted by dryland farmers to cope with the natural vagaries of the region. Dryland technologies like land conservation measures improve land productivity by managing soil, water and vegetation resources to produce perceptible changes

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with regard to water resources development in the watershed. Technologies for enhanced water use efficiency of crops grown hold importance in case of dryland agriculture so as to realize ‘more crop per drop’. Physiological and agronomic practices among others could be utilized for better crop management through adoption of suitable technologies for minimizing evaporation and transpiration losses. For dryland areas, agronomic measures such as summer ploughing, ridges and furrows, contour farming, ploughing across slopes, vegetative barriers, crop rotation, strip cropping, mulching, amendments to soil, alternate land use pattern (ALUP) and chisel ploughing are important for soil and water management. The most important soil and water management techniques in dryland areas include BBF, contour bunding, contour trenches, contour stone walls, compartmental bunding, random tied ridging, basin listing, bench terracing, microcatchments, farm ponds, percolation ponds, check dams, etc. Scheduling of irrigation, efficient use of nitrogen fertilizers, better irrigation system, etc. can lead to improved soil health and crop productivity thus providing good returns to farm household. Development of improved crop varieties with characteristics, i.e. efficient utilization of abiotic factors to maximize stable economic yield and total production, high early seedling vigour, wide crop adaptability, deep-rooted branched root system, photo-thermo insensitivity and disease resistance, is the main prospect for improving crop production under dryland conditions. Socioeconomic and personal attributes affect the adoption of sustainable technologies in dryland agriculture farmers. Adoption of evaporation and transpiration minimization technologies involves multiple trade-off and risks on the part of the farmers. Nevertheless, there exist many success stories from different developing nations of the world where adoption of sustainable dryland farming technologies resulted in enhanced productivity of crops and generated additional income for the farmers. Operational Research Project on dryland agriculture at Alanatha, Karnataka, India, from 2010 to 2014 involved opening of moisture conservation furrow between paired rows of pigeon pea in finger millet + pigeon pea (8:2) and groundnut + pigeon pea (8:2) intercropping systems which recorded higher finger millet grain equivalent yield (3156 kg/ha) and groundnut equivalent (1007 kg/ha) yield with higher net returns (37,390 and 18,842/ha, respectively) and higher values of sustainable yield index (0.56 and 0.30, respectively). Livelihood and environmental benefits were created by an experimental afforestation plantation in the semiarid Dhanawas village in Haryana, India. The plantation was carried out on 8 ha of communally owned wasteland. The plantation was a source of employment for the poorer households of the village generating 4220 days of work. Development of appropriate policies and regional strategies to ensure adoption and promotion of sustainable technologies in drylands can ensure food, nutritional and livelihood security of farm families of the region.

**Keywords**

Drylands · Dryland farming · Sustainable technologies · Adoption · Farmers · Livelihood

## 30.1 Introduction

Drylands are home to an estimated two billion people across the world, about 90% of who live in developing countries. Drylands represented 43.2% of total global area in 2020 and are predicted to be 44.2% in 2050 (FAO 2020). In drylands, agriculture depends upon the erratic weather conditions and is referred to as dryland farming. Dryland farming is the cultivation of crops without irrigation in regions of limited moisture, receiving typically less than 500 mm precipitation annually. Farmers of drylands are small and marginal in nature with poor resource base. Agriculture in drylands suffers from declining crop yields and livestock productivity with limited investment in technologies and inputs. Monocropping and tillage-based farming system, overgrazing, cultivation of soils in marginal areas and residue removal for fuel or fodder have caused severe land degradation, soil erosion and loss of fertility in drylands. The production tools and cultivation techniques used in the dryland farming are primitive, and the ability to resist pests, diseases and natural disasters is low. Human population in drylands is fret with poverty, food insecurity, biodiversity loss, frequent droughts, environmental degradation and water scarcity at critical times during agricultural seasons which are aggravated by climate change. Sustainable technologies and risk management strategies are required to be adopted by dryland farmers to cope with the natural vagaries of the region.

## 30.2 Importance of Dryland Agriculture in Ensuring Livelihood

The vital role that dryland agriculture plays in Indian economy is well recognized and duly accepted. Presently out of the total 143-million-ha cultivable land, approximately 108 million ha falls under the rainfed category and contributed about 43% of the total food production of the country. More than 50% of the oilseeds and pulse production in India comes from the production in dryland areas. With the above facts, it is very much proven how crucial role dryland agriculture is playing in securing food and nutritional security in countries like India, particularly in other parts of the world like South Asian and African countries. The thrust of agricultural development so far has largely focused on the areas which have assured irrigation facilities because of assured production and quick response. But of late the focus has been gradually shifting, the importance of dryland agriculture is being duly recognized, and a lot of resources and budgetary support are being committed by countries to the development of such regions. Some of the significant contributions and importance of dryland agriculture are being discussed here:

### 30.2.1 Helps in Ensuring the Nutritional Security

Most of the nutritionally rich coarse grains like ragi, oat, barley and maize are largely grown in the dryland area because of their less water requirement and less maturity period. The majority of the coarse grains and other oilseeds and pulse crops like bajra, maize, ragi, oat, oilseeds, jowar and cotton are produced in the dryland areas. Approximately 30% of the total rice production is contributed from the dry farming method. If we see comparatively nutrient status of millets with other major grains like rice, wheat, etc., it is amply evident that coarse grains like millets are far more nutritious than rice and wheat. Pearl millet has almost 20-fold higher iron content and three times more calcium than rice. This is very important as India has a serious problem of malnutrition like iron and calcium deficiency. Finger millet is said to have around 300 mg/g of calcium which is super high than any other crop (Kumar 2012).

### 30.2.2 Dryland Farming Helps in Reduction of Desertification Process

Since soils of regions under irrigated agriculture are facing problems of degradation due to nutrient depletion, salinity build up and overuse of chemical fertilizers; cultivation of crops such as maize, bajra, oat, mustard etc. can help in compactness of soil particles thus reducing the process of degradation and desertification.

### 30.2.3 Source of Livelihood for Large Chunk of Population

About 70% of the population lives in dry areas, and their livelihood depends upon the success and failure of the crops. Dryland agriculture covers almost 60% of the cultivated area and 40% of the human population and 60% of the animal population.

### 30.2.4 Dryland Offers Good Source of Development

The dryland offers ample opportunity for the development of social forestry, agroforestry, silviculture, horticulture and agro-silvi-pasture and other such similar systems which will not only ensure smooth and adequate supply of food for the population living in these areas but also supply fuel to the people’s fodder for the cattle. Besides ensuring food and nutritional security, dryland agri-farming system continuously helps in ecological maintenance by ensuring eco-friendly practices and forming vegetative covers.

### 30.2.5 Dryland Agriculture Is Key to Food Security

Continuous population growth is becoming a cause of concern for the future world especially in countries with less resources and more population like developing India and China. In order to ensure continuous food security for such a large part of the population, total food grain production figures should go higher and higher with the same or even less resources as compared to presently available resources. To alleviate this problem, the per unit production of all major crops must be increased significantly specifically the grain crops like rice, wheat, maize, etc. as these crops are the staple food in most of the countries. The increasing population has a direct relation with increase in the demand for more food production, and sadly, climate change has started to show its impact on the farmers, diminishing yields of the major crops under cultivation. Rice and wheat cannot perform to their potential in dryland or semiarid conditions, and hence we need to focus on crops like millets and other coarse grain crops which are well acclimatized and well adopted to dryland environment and provide good yields for farmers under adverse climatic conditions. Improving these crops for better yield will provide livelihood for the dryland farmers and also generate additional grain yield to feed the world (Taylor 2003). Surprisingly, the yield of the foxtail millet crop records as high as 10 t/ha in China which indicates the amount of scope to increase yield in India (Jiaju 1986).

## 30.3 Constraints of Dryland Agriculture

Cultivation of crops in areas where annual rainfall is more than 750 mm but less than 1150 mm is called dryland farming. Dry spells may occur, but crop failures are less frequent. Higher evapotranspiration (ET) than the total precipitation is the main reason for moisture deficit in these areas. The soil and moisture conservation measures are the key for dryland farming practices in semiarid regions. Despite several improvements over a decade in terms of irrigation, marketing, institutional support and infrastructures, dryland farmers and dryland agriculture are continuously facing several constraints and continue to operate under such constraints. Some of them are discussed here:

### 30.3.1 Prevalence of Heat and Wind

One of the most visible challenges of dryland agriculture and dryland areas is the continuous prevalence of heat and wind which increase the leaf surface temperature of the plant, thus increasing the rate of evapotranspiration. Increased rates of evapotranspiration result in loss of soil and plant moisture, which increases the irrigation demand for crops, which sometimes causes crop failure as well. High-speed wind sometimes also causes mechanical damage to crops. The effects of winds can be reduced by windbreaks and shelter belts (lines of trees perpendicular to the direction of prevailing winds). Some useful tall species are tamarisk, casuarina and eucalyptus. A windbreak can consist of trees and other plants of varying height. As a general rule, a windbreak is effective over an area two and a half times the height of the tree.

### 30.3.2 Soil and Moisture Problems

In the dryland areas of the country, soils are highly diverse in their content and characteristics. Alfisols and vertisols are predominately found in semiarid regions, whereas in river basins, alluvial soils are generally seen, and aridisols are a common phenomenon in the desert regions. Crops grown in alfisols are subjected to severe drought stress, whereas those grown in vertisols have less severity to drought, due to its better water holding capacity. Alluvial soils of arid regions have low soil fertility but respond well to inputs and are highly productive under irrigated conditions. Wind erosion predominates in arid soils.

### 30.3.3 Environmental Changes of Waterlogging and Salinity

Waterlogging and salinity problems have directly contributed to the degradation of soil and thus reduced soil fertility and its productivity. Irrigation salinity has a major impact on dryland crops. Poor drainage facilities, over irrigation of fields, improper irrigation for damaged soils, etc. are the major causes of waterlogging and salinity. All these factors cause an increase in groundwater recharge and rise in the water table, resulting in the accumulation of salts on the soil surface (www.informaction.org). These environmental changes result in reduction of yields and abandonment of lands which has facilities for irrigation. Estimates from Central Arid Zone Research Institute, Jodhpur, predict that 60% of the command areas in India will develop waterlogging and salinity problems in a decade's span.

### 30.3.4 Dietary Habits and Nutritional Characteristics of Crops Grown

The choices of the crops that are to be grown in drylands are very limited. Oilseed pulses and coarse grains like bajra, ragi and jowar are grown in drylands. Farmers have to purchase food grains and other necessary items from the revenue they obtain from the sale of the crops grown, since the dryland crops are not much remunerative, leading to an economic imbalance. Crop substitution is another alternative. Farmers possess socioeconomic reasons for growing traditional crops which are not high yielding. But when markets are developed, it can bring about changes in the food habits.

### 30.3.5 Limited and Uneven Distribution of Rainfall

Precipitation is very limited in dryland areas ranging from 750 to 1150 mm which is not sufficient for successful growth and development of the majority of the crops. Distribution of the limited rainfall is not evenly distributed; that is another major problem with the majority of dryland cultivated areas in most parts of the world, particularly in India.

### 30.3.6 Large-Scale Prevalence of Monocropping

Monocropping is one of the most prevalent features of dryland agriculture. Because of lack of assured irrigation facility and adequate and timely rainfall, the generally prevalent farming system is monocropping, since crop failure is a common phenomenon in the case of dryland agriculture.

### 30.3.7 Poor Fertility Status in Marginal Lands and Low Productivity

The prevalence of dry spells and poor organic content resulted in the poor fertility status of the dryland areas. Dryland soils are generally lacking in nitrogenous, phosphorous, potassium and carbon content which affect their fertility status.

### 30.3.8 Socioeconomic Constraints of the Dryland Farmers

The majority of the farmers in the dryland areas come under the category of the small and marginal farmers who are engaged in farming of a subsistence nature. Generally, because of the poor resource base and economic constraints, they could not introduce the latest technological intervention in their farm fields, which resulted in poor yields. Social backwardness, lack of infrastructure and adequate technical and marketing support are other major concerns of the dryland farmers. Some other major identified constraints of the dryland farming system are as follows (Goyal et al. 2016):

- Prolonged dry spells during the crop period
- Late onset and early cessation of rains
- Irregular topography with high erodibility of land
- Presence of dissolved harmful salts in groundwater
- Waterlogging in plain lands
- High movement of sand and soil particles in dryland areas
- Occurrence of extreme natural hazards like drought and rainfall

## 30.4 Soil and Water Management Techniques

Soil and water are very crucial for the survival of life on earth. These resources are essential for the human need for food, feed, fuel, fibre and water (Manivannan et al. 2017). It provides a place for plants to grow and develop (Eswaran et al. 2001). It is very important to manage soil and water in dryland areas. There are numerous climatic hazards that threaten dryland agriculture, such as droughts, floods, erratic and ill-distributed rain, undulating soils, depleting groundwater, low crop yields, etc. (Nagaraj 2013). Thus, sustainable water and soil management techniques are essential to reduce soil and water depletion in drylands. For dryland areas, the following agronomic measures are essential for soil and water conservation:

### 30.4.1 Summer Ploughing

During the summer months, the field is ploughed with special tools to break up soil crusts. By ploughing deeply and overturning the soil, piercing sunrays allow the soil crust to be disinfected (Shori et al. 2022). During pre-monsoon showers, it facilitates the recharging of soil profiles. The soil is soaked up with water and runoff is reduced, as well as pests and weeds are reduced. It is recommended to pulverize the soil and prepare the field for sowing or transplanting prior to monsoon by using a harrow or cultivator (Benal et al. 2010). By breaking down the upper crust of the soil, plough in the summer provides greater in situ moisture conservation by increasing soil infiltration capability and permeability (Lavanya and Anamica 2013). It improves the soil structure due to alternate drying and cooling. Increasing the soil's ability to absorb rainwater increases the amount of atmospheric nitrate that enters the soil and increases soil fertility (Singh et al. 2004a, b). Through ploughing of fields across slopes, a reduction in the soil capacity to carry runoff water is achieved (Shehrawat and Singh 2003). So, water erosion of soil is restricted. The land is more than half covered with clods, which can limit nutritive soil particles from being eroded by the wind.

### 30.4.2 Ridges and Furrows

It acts as a continuous barrier to downward movement of water, so infiltration is increased (Mallikarjunarao et al. 2015). As a result, soil fertility and crop yield are increased due to a lowered loss of soil and nutrients (Li et al. 2020). There are several methods of conserving soil and water in situ for black and red soils, and ridges and furrows are one of them. Studies have shown that up to 15% higher yields are achievable when using these techniques (Magray et al. 2014).

### 30.4.3 Contour Farming

It is a farming method with rows that run nearly level around the hill instead of up and down. During rainy weather, soil is eroded, nutrients are removed, and seeds are removed. The free movement of water downward is prevented by ridges and furrows, which act as continuous barriers (Somasundaram et al. 2014). This results in a greater reduction in soil erosion along with an increase in soil fertility and crop yield (Ramanjaneyulu et al. 2020). It consists of ploughing, planting and weeding along the contour of the land. As contour lines cross the slope, they will run closer together on part of the hill and further apart on part of the hill that has a gentle slope. Contour farming alone can reduce soil erosion by as much as 50% on moderate slopes, and it promotes better water quality and provides 10–15% additional yield (Taley 2011).

### 30.4.4 Ploughing Across the Slope

Throughout the slope, water flows down with greater velocities, resulting in the need for more water energy to carry top soil. Farmers suffer two major losses resulting from reduced in situ moisture conservation and eroding top soil nutrients (Kisic et al. 2002). To accomplish this, plough the sloppy soil across the slope (Kouselou et al. 2018). In situ, it conserves moisture and prevents fertilizer and plant nutrients from washing out during irrigation. The energy of flow is reduced; erosion of topsoil is drastically reduced (Ivica et al. 2018). Plant nutrients and water are more readily available, resulting in an increase in crop production.

### 30.4.5 Vegetative Barriers

Planting of grasses or shrubs on the slope to slow it down and catch the sediments that are being eroded (Sivanappan 1995). It is possible for soil to accumulate behind the strip after a period of time. It yields good benefits in the dryland soils. When it rains heavily, barriers prevent runoff from carrying soil from the land (Wolka et al. 2018). By reducing the velocity of water flow, it prevents soil erosion and conserves moisture. The rate of infiltration increased with a reduction in runoff velocity; only clear water escapes from the land (Kpadonou et al. 2017). They can be easily maintained once they are established.

### 30.4.6 Intercropping

This is the practice of growing several crops concurrently on the same piece of land, in a definite row pattern. For example, growing maize + black gram in 1:2 ratio, i.e. after every one row of maize, two rows of black gram are sown (Lu et al. 2010). Roots of intercrops could exploit the full water potential of croplands. In addition, it limits excessive transpiration between the rows and reduces interrow evaporation. Maintaining a microclimate that is favourable and suitable to plant growth and development is the purpose of it (Palaniappan et al. 2009). It helps to increase the crop yield per unit area greatly without increasing water consumption, so as to promote crop water use efficiency effectively (Maitra 2020).

### 30.4.7 Strip Cropping

It is the practice of growing field crops in narrow strips either at right angles to the direction of the prevailing wind or following the natural contours of the terrain to prevent wind and water erosion of the soil (Unger et al. 1991). It combines the soil and moisture, conserving water, and is more effective in reducing soil loss. It is a kind of agronomical practice where crops are planted in the form of relatively narrow strips (6–10) across the land slope (Bhattacharyya et al. 2016). These strips are so arranged that the strip crops should always be separated by strips of close-growing and erosion-resistant crops. It is the most effective method to control soil erosion in certain types of soil and topography (Sivanappan 1995). Strip cropping is a more intensive practice for conserving rainwater to check the surface runoff and force it to infiltrate into the soil, thereby facilitating the conservation of rainwater. Strip cropping is suitable for soil conservation in those areas where the length of slope is not too long. Strip cropping practices reduce the rate of soil erosion from water and wind due to reduction in runoff velocity (Sivanappan 1995). These practices are helpful in increasing the infiltration rate of the soil under cover condition. It reduces the transport of sediment and other waterborne contaminants. It improves the water quality and protects growing crops from damage by windborne soil practices (Ramakrishna and Rao 2008).

### 30.4.8 Mulching

It is one of the best and easy practices to conserve the soil moisture in dryland areas. In this practice the mulch which may be material (polythene, straw, etc.) is placed on the soil surface (Sharma et al. 2011). It helps to maintain moisture, reduce weed growth, mitigate soil erosion and improve soil conditions (Zhang et al. 2009). Mulch simply acts as a protective cover of material that is spread on the top of soil to prevent the upper most layer of soil from blowing and being washed away due to runoff or high wind velocity. Mulch can either be organic such as grass clippings, straw, bark chips and similar materials or inorganic such as stones, brick chips and plastic (Liu et al. 2015). Conservation tillage is a common practice that creates mulch on the soil surface. It leaves the crop residue on the top of the soil as mulch. So, basically, this practice is beneficial in improving soil structure, increasing infiltration capacity, conserving soil moisture, reducing soil erosion, checking weed growth, checking nutrient losses and enriching soil by adding organic matter to the soil (Wang et al. 2012). It is also helpful in the reduction of compaction of soil due to heavy rains. The crop residue which was used as mulch prevents soil evaporation (Bhatt and Khera 2006).

### 30.4.9 Alternate Land Use Pattern

Drylands may not be suitable for crop cultivation and then may be used for pasture management, tree farming, ley farming, dryland horticulture and agro-forestry systems including alley cropping (Chary et al. 2012). All these systems which are alternative to crop production are called alternate land use systems (Reddy and Singh 2002). Agro-forestry is an important farming practice in dryland areas where agricultural crops are grown with trees on the same piece of land. It provides food, fodder for cattle, furniture wood and fuel, checks soil erosion, controls wind velocity to reduce crop damage, regulates soil temperature and develops the environment and enriches the soil (Radhamani et al. 2003). It increases the gross income of the land.

### 30.4.10 Broad Beds and Furrows

Broad bed furrow system (BBF) is a water management technique where runoff water is diverted into 30 cm wide and 30 cm deep field furrows (Anantha et al. 2021). The field furrows are blocked at the lower end. When one furrow is full, the water backs up into the head furrow and flows into the next field furrow. Between the field furrows are broad beds about 170 cm wide, where crops are grown (Selvaraju et al. 1999). The most important function of BBF is to control erosion and to conserve soil moisture in the soil during rainy days. It is suitable when the slope of the land is <3% (Singh and Jain 1990). The broad bed and furrow system is laid within the field boundaries. It controls soil erosion and conserves soil moisture in dryland (Singh et al. 2021). It acts as a drainage channel during heavy rainy days.

### 30.4.11 Contour Bunding

Contour bunding intercepts the runoff flowing down the slope by an embankment (Tripathi 2014). It helps to control runoff velocity. It can be adopted in light- and medium-textured soils. It can be laid up to 6% slopes (Mallikarjunarao et al. 2015). It helps to retain moisture in the field (Shori et al. 2019).

### 30.4.12 Contour Trenches

It was suitable where the slope of the land is >33.33% (Singh 2009). It helps to reduce the velocity of water and checks soil erosion. Trenches are excavated in contours with dimensions of $2 \times 1 \times 1\ m^3$, and excavated soil is used to form bunds in the down line (Singh et al. 2014). The trenches were formed at 5–10 ft vertical distance (Mishra and Tripathi 2013).

### 30.4.13 Compartmental Bunding

Compartmental bunding means the entire field is divided into small compartments with a predetermined size to retain the rainwater where it falls and arrests soil erosion (Pauline et al. 2020). The compartmental bunds are formed using bund former. The size of the bunds depends upon slope of the land (Selvaraju et al. 1999). Compartmental bunds provide more opportunity time for water to infiltrate into the soil and help in conserving soil moisture (Patil et al. 2016). It is an effective moisture conservation measure in dryland. It is suitable for lesser rainfall areas, and the slope is <1% (Sivanappan 1995). Small compartments act as a dam and store the rainfall received in the compartments for longer periods. It increases the water holding capacity of the soil (Selvaraju et al. 1999). It can be formed while ploughing itself or before early sowing. It reduces the formation of cracks and helps to overcome the disadvantages of contour bunding (Patil and Sheelavantar 2004).

### 30.4.14 Random Tied Ridging

Using this system, the ridges are vertically tied at relatively short intervals to form rectangular structures that harvest water (Selvaraju et al. 1999). When rain falls heavily, it facilitates the infiltration of water into the soil (Vinotha et al. 2021). Water infiltration into the soil is facilitated by the slight sloppiness of the tied ridges (Devaranavadagi and Bosu 2018). The various in situ methods of harvesting water in black or red soils, such as summer ploughing, broad bed and furrows, ridges and furrows, compartmental bunding, etc., have the potential to increase crop yields by as much as 15% (Sivanappan and Panchanathan 1985). It conserves soil moisture and soil in red soils (Selvaraju et al. 1999).

### 30.4.15 Basin Listing

An implement called a basin lister is used to construct the basins in this method for soil and water conservation (Muthamilselvan et al. 2006). These basins are constructed across the slope (Muthamilselvan et al. 2006). This allows rainwater to infiltrate into the soil for the longest possible time (Selvan et al. 2012).

### 30.4.16 Microcatchment

Developing microcatchments around trees is an effective way to improve the storage of rainfall in drylands, since drylands do not receive sufficient rainfall for cultivation of crops (Shangguan et al. 2002). It is possible to develop this type of catchment system on sloped land. For tree crops, according to interspace, available catchments are formed (Sivanappan 1995). Rainwater is stored in it and helps trees grow (Wani et al. 2009).

### 30.4.17 Percolation Ponds

A percolation pond is a small pond used to collect runoff of rainwater and to allow it to flow downward and sideways. They are usually found in low-lying areas of land (Sivanappan 1995). It is preferable to use deep ponds since there will be less evaporation of the water stored there. The rainy season replenishes the groundwater.

Consequently, it reduces soil erosion by reducing the velocity of water (Sivanappan and Panchanathan 1985). Besides reducing siltation in water tanks, ponds and check dams, it also reduces flooding (Gunnell and Krishnamurthy 2003).

### 30.4.18 Check Dams

The check dams constructed across gullies act as mini percolation ponds to harvest water (Agoramoorthy et al. 2008). A series of check dams can assist in augmenting the filling of existing wells nearby on both sides of a gully regardless of their primary purpose of controlling the development of gullies (Agoramoorthy and Hsu 2008). In order to prevent gully formation, contain soil erosion and replenish groundwater, check dams should be constructed at intervals that are appropriate (Agoramoorthy et al. 2016). As a temporary measure, it can be built with stones, bamboo and wooden planks or as a permanent concrete structure (Dashora et al. 2018). Water infiltration and runoff control are achieved by check dams, as well as recharging (Boix-Fayos et al. 2007). Water can soak into the soil more fully with check dams because they provide adequate time and space (Daftary 2014).

## 30.5 Crop Production Technologies for Dryland Areas

In the case of dryland farming, growing season is short, whereas in rainfed farming, it is longer, and double cropping is possible depending upon the moisture holding capacity of soil. However, both are used synonymously, and in both cases, management of moisture is of great significance for raising crops successfully.

In the event of low rainfall with its uneven distribution in dryland areas, certain resource-conserving techniques are found to be effective in reducing the effect of water stress on plants and enhancing crop productivity. Collection of rainwater (in situ and ex situ), conservation of soil moisture and reducing its losses and efficient utilization of available soil moisture for crop plants could be effective strategies for overall productivity enhancement in dryland areas. The following are some of the resource conservation strategies:

### 30.5.1 Crop Management Practices

Tillage: Fallowing, deep ploughing, deep summer ploughing, dust mulch, weed control, optimum plant density, optimum planting system and row sowing and leaf stripping reduce the transpiration.

### 30.5.2 Soil Management

For crop cultivation in dryland areas, soil management techniques like addition of crop residue and organic matter, mid way correction and use of polymers can be adopted.

### 30.5.3 Use of Mulches

Mulch is any material applied on soil surface to check evaporation and improve soil water. Application of mulches results in additional benefits like soil conservation, moderation of temperature, reduction in soil salinity, weed control and improvement of soil structure.

### 30.5.4 Use of Anti-transpirants

Stomatal resistance slows down simultaneously transpiration and CO assimilation. It has been observed that the best two anti-transpirants reduce transpiration 30–40% at the most.

1. *Anti-transpirant*: It is any material applied to transpiring plant surface with the aim of reducing water loss from plant. The objective of anti-transpirant is to reduce the rate of transpiration that has low or little effect on photosynthesis. It induces plant to offer more resistance to loss of water vapour through stomata but relatively lower resistance to CO entry.
   (a) Induced stomatal closure: Spray materials used for various purposes such as herbicides, fungicides, metabolic inhibitors and growth hormone have been found to cause closure of 'guard cells' of stomata and thereby reduce transpiration.
   (b) Film-forming anti-transpirants: Plastic and waxy materials reduce both transpiration and photosynthesis. These are more permeable to water vapour than carbon dioxide.
2. *Increasing leaf reflectance*: Reflecting materials reduce energy load on leaves by increasing albedo. They also reduce leaf temperature, for example, kaolin and white wash.
3. *Growth retardants*: Like cycocel, there is an increase in root growth which results in considerable delay in senescence of leaves, and as a result of increased root length, the plants are able to withdraw water from deeper layers of soil. Wind breaks: The wind breaks have found their utility in reducing transpiration losses under field conditions. It has been seen that the yield of grain crops increases by 20–30% and that of grasses by 100–200% in sheltered zones.
4. *Moisture utilization through*: Moisture can be effectively utilized through selection of crop and varieties, Timely sowing, Sowing method, Seed rate (25% more), Fertilizer dose (Half of normal dose), Seed hardening (with KNO), Weed control,

Optimum plant population, Lifesaving irrigation and Timely harvesting of kharif crops. A harvest of 4 weeks later than normal may result in uneconomic crop yields. Under these circumstances, the following late varieties can be cultivated to get a relatively higher yield.

| Centre | Crop | Normal | Late |
|---|---|---|---|
| Akola | Sorghum | CSH-5/CSH-9 | CSH-1 |
| Punjab | Wheat | PBW-527, PBW-175 | PBW-373, TL-1211 |
| Hisar | Green gram | Varisha | |
| Jhansi | Sorghum | CSH-5 CSH-6 | SPV-224 |
| Udaipur | Maize | Ganga 5 | Bassi selected Agati |

5. *Transplantation*: In some of the crop, nurseries have to be raised in a place where water is available and transplanting can be done with the onset of rain. It's a sure way of compensating for the delay in commencement of sowing, although transplantation is a labour-intensive operation and it may not be possible to go for transplantation for all crops. For example, finger millet transplantation at Bangalore during the month of September yielded as high as 25.6 q/ha whereas directly sown yield only 7.5 q/ha. Under transplantation conditions, crops get a longer time for their growth as compared to direct seeding.
6. *Alternate crop/variety*: Certain crops are more efficient either due to their shorter duration or capacity to produce better yield under relatively unfavourable moisture regimes when sown late in season. For example, cereal crop in general is less tolerant to drought conditions than legumes or oilseed crops. For example, it is now well established that the caster variety Varuna produces more yield in red soils of Telangana region as compared to pigeon pea under late sown conditions. In western Rajasthan, short-duration crops like green gram and cowpea have been found to perform better than pearl millet under late sown conditions. There are some examples which illustrate that varieties sown under normal conditions are different than those of late sown conditions.

## 30.6 Dry Spells Immediately After Sowing

During some years, a dry spell may occur immediately after sowing of the crop. It may result in poor germination due to soil crusting, withering of seedlings and poor establishment of crop stands. It's always necessary to maintain proper plant stands to ensure better yield.

## 30.7 Break in Monsoon, Mid-season or Late

Sowing of alternative crops and varieties is the established approach to minimize risk of total crop failure over traditional crops and varieties but once crop is growing there could be moisture stress due to mid season drought. The water requirement of crops depends upon solar radiation intercepted by the crop canopy. For example, if drought conditions occur 40–50 days after sowing, the leaf area development will be maximum, leading to fast depletion of soil moisture. Therefore, reduction in LAI by either pruning or ratooning of crop mitigates adverse effect of drought to a certain extent. Ratooning of a drought-affected sorghum crop with subsequent rain gave 8 q/ha of grain yield over 2 q/ha without ratooning. Similarly, pearl millet gave 25.1 q/ha with ratooning while non-ratoon crop gave 15.0 q/ha. For indeterminate crops like castor, pigeon pea, etc., drought-affected plants have been found to have higher yields, if 2% spray of urea was done after receipt of rainfall. In the case of mid-season drought, interculture is done, as it helps in soil mulching which reduces loss of moisture through evaporation. If some mulching material is put in between rows of crops so as to help reduce evaporation loss from soil and also conserve moisture, it can be utilized by succeeding rabi crops. For example, in the Kandi areas of Punjab, mulch of Bersooti is useful for maize crop and maize stover/stalk for retaining more moisture for the succeeding rabi crop. Weed control under mid-season drought conditions is useful because removal of weeds is helpful for conserving more moisture for main crops instead of its wastage by unwanted plants.

## 30.8 Techniques to Reduce Evapotranspiration Loss and Improve Water Use Efficiency

Efficient use of available water is crucial considering the present climate change scenario in dryland areas where water resources are scarce, thus jeopardizing agricultural production and food security in future times. In such types of situations, cultivating crops with higher water use efficiency (WUE) can turn out to be a good option. Techniques for reducing evapotranspiration losses include crop improvement, weed management, nutrient management, adjusting planting calendar and changes in irrigation and seeding rates, among others (Liu et al. 2016; Ma et al. 2018). Thus, improvement in WUE for reducing evapotranspiration losses is vital under different agro-climatic conditions especially in arid regions to realize sustainable agricultural production. A brief description of the techniques to reduce evapotranspiration losses and improve water use efficiency is as follows:

### 30.8.1 Mulching

As already discussed, mulching is an important management technique to minimize evapotranspiration and one of the most economical and efficient techniques for controlling soil evaporation. Several studies have shown that mulching practices can improve the WUE of the field crops. Zhang and Oweis (1999) and Ram et al. (2013) reported rice straw mulching on wheat crop increasing WUE by 10% and 14.7–34.2%, respectively.

### 30.8.2 Soil Fertility Management

Soil fertility management is a critical factor that influences WUE of field crops. Soils enriched with balanced macro- and micronutrients are critical for achieving higher yields from every drop of irrigated water. Ul-Allah et al. (2015) found the effect of fertilizer application was more prominent in water-limited conditions rather than irrigated and water-stressed soils. Studies by Khan et al. (2003) and Hussain et al. (2018) reported potassium and zinc can ameliorate effects of drought and also improve WUE of crops grown in normal and water-stressed conditions. Martineau et al. (2017) observed optimum application of potassium had improved tolerance of maize crop to drought effects by 30% higher WUE due to lower leaf evapotranspiration. Potassium application also causes leaf rolling, thus reducing evapotranspiration and saving water.

### 30.8.3 Genetic Improvement of Crops

Agricultural experts have developed several crop varieties possessing improved WUE in the aspects of increased yield and carbon dioxide fixation (Krupnik et al. 2012; Ul-Allah et al. 2018). Usually, significant genetic variation has been observed among crops and also within genotypes of the same crop in terms of WUE. Studies on chickpea genotypes by Pang et al. (2017) stated that those chickpea genotypes with lower transpiration losses during early stages of drought stress and higher losses at later stages were more tolerant to drought with higher WUE, whereas other chickpea genotypes with similar transpiration rates throughout the drought stress period were less drought tolerant with lower WUE. Wang et al. (2016) reported that wheat crop variety JM22 had higher WUE (4.2–9.3%) than WM8 and HS4399 due to better water suction capacity from deeper soil and better biomass accretion post-anthesis. Different breeding techniques to improve WUE of crops genetically are evaluation and selection of genotypes, identification of suitable traits and utilizing wild relatives so as to incorporate new genes for enhancing WUE (Wang et al. 2016; Pour-Aboughadareh et al. 2017). Since wild relatives of crops have biotic and abiotic stress-tolerant traits, they are well adapted to varied climatic conditions. In this perspective, traits significant for higher WUE can be used to develop novel genotypes through interspecific breeding.

### 30.8.4 Seeding Rate and Planting Pattern

Improving WUE of various crops is also dependant on seeding rates and planting pattern. If plant population is above optimum, then competition for water, nutrient and space hampers production potential. On the other hand, if plant population is below optimum, then production per area would be low due underutilization of space and resources. Planting geometry is an important parameter for WUE. Compared to flat sowing, bed and furrow sowing can result in effective use of water. Ma et al.

(2018) reported increased seed rates in wheat resulted in reduced WUE due to elevated depletion of soil water. Hu et al. (2018) reported higher seeding rate in wheat during water-scarce condition, leading to increased evapotranspiration losses and reduced production. Similarly, Wang et al. (2017) reported the WUE of wheat increased with an increase in sowing rate when sowing time got delayed.

Planting pattern affects growth and development of crop due to its impact on sunlight exposure, root growth, shading effects and saving water in order to reduce evaporation. For example, Soomro et al. (2017) reported that wheat crop sown on raised bed had 54.4% higher WUE than those sown on flat surface since water consumption by the crop was reduced by 50.7%. A similar study on sunflower crop by Hussain et al. (2010) reported ride sown sunflower had more WUE compared to flat sown crop. A similar study by Khan et al. (2012) found ridge-sown maize crop had higher WUE than flat sown ones due to a well-developed root system with deep roots for more water uptake capacity from soil.

### 30.8.5 Planting Calendar

Altering the sowing dates of crops in accordance with conducive growing conditions is an important management strategy for improving WUE. Studies have indicated appropriate time of crop sowing can improve WUE (Abdou et al. 2011; Ma et al. 2018). Research studies have observed that early sown crops have higher WUE due to longer life cycle compared to late sown crops. A study by Feyzbakhsh et al. (2015) on maize crop under semiarid conditions revealed that late sown maize had better grain yield compared to early sown one due to better soil water management. Crops usually have specific sowing times; thus, the planting calendar of crops should be carried out in such a way so as to achieve maximum output per drop of water and also to save water for future generations from a sustainability point of view. In addition to late sowing which reduces yield and WUE, the type of crop and prevailing climatic conditions also affect decisions of farmer on sowing times either early or late.

### 30.8.6 Water Management

WUE of crops can be improved by reducing the number of irrigations. Limiting the number of irrigations encourages roots to explore deep layers of soil, thus increasing water uptake and reducing leaf canopy area and transpiration losses (Xu et al. 2016). Irrigating crops only at critical stages is a viable option to increase WUE. Frequent irrigation of wheat and barley crops at 75% ASW depletion produced a lower WUE rather than irrigating the crop at critical stages. Ram et al. (2013) studied that irrigating the wheat crop at two critical stages, crown root initiation and booting, had higher WUE, and with subsequent irrigations, the WUE declined steadily. This may be due to less biomass portioning to grains at more frequent number of irrigations. The yield increase due to frequent irrigation does not correspond to the additional water used. Modern technological advancements with the use of GPS-based drip and sprinkler irrigation systems can result in effective use of water by applying water according to crop and soil needs. Adoption of alternate wetting and drying methods of rice production, modern techniques of irrigation and deficit irrigation management would improve the WUE of the crop rather than the conventional transplanted rice cultivation.

### 30.8.7 Weed Management

Weeds are those unwanted plants that negatively impact the growth and yield of the crop due to competition for space, water, nutrients and sunlight, thus having the ultimate effect on WUE. Subramanyam et al. (2007) stated that controlling weed infestation would significantly increase yield due to improvement in water and resource use efficiency. But controlling weeds is a difficult task as they grow fast and possess wide genetic diversity. A study by Blubaugh et al. (2016) found cultivating cover crops with the main crop increased the population of beneficial omnivores which are natural enemies of weed plants as they reduced the weed population by 73%. Allelochemicals present in crop plants can also be used to control weed infestation which is a sustainable way of integrating weed management. Manual weed is also an ecological method, but it is time-consuming to cover large areas and a difficult task due to shortage of labour supply. An alternative to manual weed control is tractor-mounted mechanical weed control which is carried out in row sown crops. Usually, weedicides are used to control weeds as they are most effective, but they have detrimental effects on the environment and soil health. With hand weeding and use of pre- and post-emergence herbicides, WUE of crops like rice and wheat can be increased by 12–91.5% (Khawar et al. 2012; Verma et al. 2015). Integrated weed management practices are advisable to control weed infestation in a sustainable manner since it improves WUE of field crops irrespective of weed control methods and growing conditions of the crop.

Since different practices could be followed to increase WUE of field crops, choice and selection of methods depend on a number of factors. The most important factor is whether the method is economical or not compared to profits realized. Also, different management strategies may not be suitable for all growing conditions and areas, and a combination of management strategies may not be economically feasible also. Economic feasibility vis-à-vis reducing evapotranspiration may be termed as the increase in production of the crop due to a particular management strategy compared to the cost incurred in that strategy. Genetic improvement of crops is a sustainable and efficient method of increasing WUE of different crops as the cost is incurred only in developing suitable varieties, and after the development of the variety, no other cost is involved except for seed production. Altering the sowing times, planting calendar and seed rates is another cost-effective management strategy in increasing WUE of crop plants. Thus, selection of appropriate management strategies is crucial to maximize the yield and in turn profitability of crop cultivation.

## 30.9 Factors Affecting Adoption of Improved Farm Technologies

Use of improved farm technologies for controlling evapotranspiration losses is advantageous as it improves WUE thereby crop yield. But most of these technologies are either unavailable or not feasible to the majority of resource-poor rural households in arid regions.

### 30.9.1 Socioeconomic Factors

In arid regions, crop production is directly linked with water availability, and long spells of water scarcity necessitate farm technologies' adoption to improve WUE and the income of farm households. Mulching which is a cost-effective measure could be advised to farmers to reduce evapotranspiration losses in arid zones. Propper et al. (2010) stated that since farmers in arid regions rely heavily on agriculture, productivity of crops and land holds significant importance. But due to water scarcity and reduced yields due to drought incidences, displacement of people and deagranization are common phenomena due to the low economic viability of crop production. The extent of adoption of improved farm technologies such as crop varieties resistant to drought is directly linked with the land holding of the farmer and their participation in different farm organizations (Cavatassi et al. 2011; Kalinda et al. 2014). Raghavendra and Suresh (2018) reported that different socioeconomic factors affect the adoption of micro-irrigation techniques such as drip and sprinkler irrigation system. The significant factors were size of land holding, participation in different farmer organizations and share of irrigation.

### 30.9.2 Variation in Climatic Conditions

Climate variability over long time periods has a significant impact on crop cultivation due to increase in temperature and water availability, among other factors. Climate vagaries also result in long dry spells with drought conditions or intense rainfall which is an issue in the case of arid regions (Reyer et al. 2013). Management practices like altering sowing dates, planting calendars and weed populations have been greatly affected by variation in climatic conditions. Climate and crop data could be used to forecast future incidences of climatic variability, thus enabling farmers to adopt suitable farm technologies to reduce evapotranspiration losses.

#### 30.9.2.1 Accessibility to Farm Technologies

A study by O'Callaghan (2016) found that majority of farm households cultivating crops in dryland areas still use old farming methods, as a result of which crop failure is a common phenomenon. These traditional methods can produce a limited amount of crop yield which is a hindrance towards food security with a rising population. For the crop farmers in arid regions, Corbeels et al. (2014) recommend conservation agriculture to increase profitability and reduce evapotranspiration through minimum tillage and soil covering. Many times the improved farm technologies to reduce evapotranspiration may not be followed by the farmers in dryland areas due to subsistence farming, unfamiliarity with the technologies and lack of awareness (Sarcheshmeh et al. 2018).

#### 30.9.2.2 Marketing Linkages

Water scarcity is a major issue for crop cultivation in arid regions. But the problem grows manifold with poor marketing linkages, thus reducing profitability. Dixit et al. (2013) observed the lack of formal relations and participation in farmer organization as a hindrance towards marketing the produce. Since the farmers in dryland areas are subsistence in nature, realizing profitability is difficult, albeit in seasons of excess of produce. Thus, establishing strong marketing linkages is required as the majority of dryland farmers rely on agriculture (Sethi and Sharma 2011).

#### 30.9.2.3 Institutional Support

Adequate support from different institutions affects the rate of adoption of farm technologies. But the farmers in dryland areas often receive limited support from agricultural institutions since the institutions are poorly funded and lack infrastructural facilities (McGuire and Sperling 2013). Seed aid and seed production and dissemination of improved ones are also issues in dryland areas, and as a result of which, farmers plant poor quality seeds with below par yield. Seed aid provides temporary relief to farmer from crisis situations in case of dry spells to minimize agricultural stress. Thus, gaps are created in efforts in the transfer of improved farm technologies to mitigate the effects of water scarcity and climate due to weak institutions in dryland regions (Colville and Pritchard 2019).

## 30.10 Adoption of Sustainable Dryland Technologies: Successful Case Studies from Developing Countries of the World

Though several factors affect the ultimate adoption of any technology by farmers, there are several successful cases where increases in production of crops, improvement in livelihood and income of farmers have been reported from many developing nations of the world where small and marginal farmers are in the majority. Some successful case studies have been discussed below:

**Case 1** Karnataka state of India is a semiarid tropical region with 116.71 ha under cultivation comprising nearly 75% of the cultivable area under rainfed. About 57% of food grain production of the state comes from rainfed areas, while 97% of total pulses and 80% oilseeds are produced in dryland areas. Traditional farming systems there were less productive and could not ensure livelihood and food security and sustainability. Hence, sustainable technologies for improving productivity and livelihood security were started through an Operation Research Project (ORP) on dryland agriculture from 2010 to 2014 at Alanatha cluster of villages in

Kodhallihobli of Ramanagara district of Karnataka state. Sustainable dryland practices were demonstrated to farmers, and their adoption led to improvement in productivity and sustainability of dryland farmers. The technologies adopted were opening of moisture conservation furrow in finger millet + pigeon pea (8:2) and groundnut + pigeon pea (8:2) intercropping which led to higher finger millet grain equivalent yield (3156 kg/ha) and groundnut equivalent (1007 kg/ha) yield with higher net returns (Rs. 37,390 and Rs. 18,842/ha, respectively); intercropping of pigeon pea + field bean (1:1) resulting in higher pigeon pea equivalent yield (1173 kg/ha) and net returns (Rs.32,415/ha); adoption of improved varieties of finger millet, pigeon pea and chilli varieties according to the sowing window; and integrated nutrient management in finger millet and site-specific nutrient management in groundnut + pigeon pea as a nutrient management strategy which gave maximum net returns (Rs.36,504/ha) and pre-emergent application of alachlor at 2.5 l/ha with one hand weeding in groundnut + pigeon pea (8:2) which led to lower weed menace and higher groundnut pod yield (499 kg/ha) (Ramachandrappa et al. 2015).

**Case 2** The livelihood and environmental benefits created by an experimental afforestation plantation in the semiarid Dhanawas village in Haryana, India, were a success (Pal and Sharma 2001). The plantation was carried out on 8 ha of communally owned wasteland, which was primarily used for grazing because it was unsuitable for vegetation because of a heavy deposition of salts. In the first 2 years of this project, 12 species were planted with the primary objective of rehabilitating the degraded land. Despite initial reservations, community participation in the management of the plantation gradually increased with time. Because the plantation was a communal resource, the money generated from the harvest of wood was invested in improving the infrastructure of the Dhanawas via the construction of biogas plants. The plantation was a source of employment for the poorer households of the village and generated 4220 days of work. Also, the nutrient status of the soil improved significantly with time as the level of available soil phosphorous and organic carbon increased because trees continue to cover the top layer of the soil after harvest. Finally, the increase in litter and nutrient cycling reduced the soil pH, making it more conducive to plant growth.

**Case 3** In China, water-harvesting agriculture has been routinely used in the Loess Plateau over the past 10 years to counter the periodic seasonal droughts and erratic rainfall of high intensity and short duration with high surface runoff. In this system, water is harvested from surface runoff of roads and collected in concrete yards on plastic sheets. Water storage cellar tanks exist for harvesting runoff to provide life-saving irrigation. Agronomic measures of high water use efficiency like drip, hole, subsoil and super-sheet irrigation are practised. In the field, microcatchments are established for water harvesting and conservation to increase fallow efficiency in rainy seasons. Using the stored runoff water to irrigate the mulched winter wheat and spring corn, as well as vegetables and fruit trees, significant yield improvement and water use efficiency were reported. Plastic mulching for increasing fallow efficiency in rainy seasons and improving the yield of the next winter wheat crop was developed and demonstrated. These techniques helped in soil and water conservation and reduction of droughts in dryland farming regions (Shangguan et al. 2002).

## 30.11 Conclusion

This book chapter presents the concept about the dryland agriculture and sustainable technologies suitable for dryland. Approximately 68% of India's cultivated area is devoted to drylands, and 40% of the country's population, as well as 60% of its livestock, lives there (Singh et al. 2004a, b). A focus on dryland agriculture is needed to ensure a balanced development of the country. Dryland regions contribute significantly to pulse, oilseed, coarse grain and cotton production. Optimal use of dryland technologies for increased agricultural production can help to fill the demand-supply gap in pulses and oilseeds production and improve the economic status of farmers. The use of dryland agriculture can thus help combat malnutrition in poor areas. In addition to these, advancing the development of an institutional framework, improving credit access and extending crop insurance as well as launching on-farm research and pilot projects involving farmers' participation should also be on the agenda.

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# Challenges and Prospects in Managing Dryland Agriculture Under Climate Change Scenario

# 31

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and Aribam Ponika Devi

## Abstract

Dryland agricultural system is dependent on the vagaries of weather, especially the rainfall. It comes under the danger of extreme climate changes and unsustainable management practices. Climate changes in the form of rise in temperature, $CO_2$ level, variability of rainfall, etc. greatly affect this farming system, being a system of agriculture that demands water conservation in all practices throughout the year. Careful management of the region's agricultural resources is already required in order to ensure food security and reduce poverty, hunger and malnutrition in the ensuing decades. Variable and low yields as well as significant fluctuations in farmer's income are caused by the variability in precipitation and the poor quality of many arid-zone soils. Technology-based cropping systems for water conservations, integrated nutrient management, proper crop protection, proper land use, precision agriculture and strategies including change in sowing date, appropriate choice of cropping systems and crops are required to mitigate challenges in managing dryland agriculture under the changing climate scenario.

## Keywords

Climate change · Dryland agriculture · Management · Crop diversification · Precision agriculture

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## 31.1 Introduction

Dryland farming is an agricultural system which is solely reliant on the whims of weather, specifically the rainfall. According to UNESCO 2009, dryland agriculture makes 80% of the world's cultivated land and backs up to 60% of the total production of food crop. It includes all features of land usage under semi-arid environments in its widest sense. Considerations must be made for not only how to farm but also how much and whether to farm. Above all else, it must emphasize the capture and efficient use of rainfall. Although this is a serious misunderstanding, rainfed farming and dryland farming are frequently used interchangeably. They both exclude irrigation, but beyond that, they can differ significantly. Dryland farming a special case of rainfed agriculture in arid and semiarid regions has annual precipitation about 20–35% of potential evapotranspiration. It is inherently fragile. Conditions of moderate-to-severe moisture stress occur during a substantial part of the year, greatly limiting yield potential, and in which farming emphasizes water conservation in all practices throughout the year. There are three components of a successful dryland farming system, namely, retaining the precipitation on the land, reducing evaporation from the soil surface to increase the portion of evapotranspiration used for transpiration, and utilizing crops that have drought tolerance and that fit the precipitation patterns. Although these components have been known for centuries, new technologies continue to be developed that increase crop production in water-short areas. The variability in precipitation and at low quality of many arid-zone soils leads to variable and low yields and large fluctuations in farmers' income. Farmers have always sought insurance against such variations, in particular against catastrophic years that could bring about famine and migration (Loomis 1983). The primary management goal over the years has been to prevent crop failure, which accounts for the conservative nature of many of the strategies used by dryland farmers. Management practices designed with the objective of avoiding crop failure tend to leave resources unused in the good years because they do not fully exploit the favourable conditions that periodically arise due to weather or soil variations. Nevertheless, risk avoidance strategies are needed to minimize threats to the sustainability of the system; thus, there has to be a balance between the measures aimed at increasing productivity and those designed for ensuring sustainability.

## 31.2 Impact of Climate Changes on Dryland Agriculture

According to the United Nations, climate change refers to long-term shifts in temperatures and weather patterns. It is about nonnormal variations to the climate and the effects of these variations on other parts of the globe. These shifts may take tens, hundreds, or perhaps millions of years. But increased in human activities such as industrialization, urbanization, deforestation, agriculture, change in land use pattern, etc. leads to rapid change in global climate scenario. The impact of global climate change in the last few decades due to droughts, floods, and heat waves has greatly affected the agricultural production in terms of reducing crop yields and nutritional quality. The effects are unevenly distributed across the world and are caused by changes in temperature, precipitation, and atmospheric carbon dioxide, $CO_2$, levels due to global climate change (Mbow et al. 2017). It has been predicted in 2019 that global crop production will decline by 2–6% and food prices will rise by 80% by 2050 (Flavelle 2019) which will likely lead to food insecurity, disproportionally affecting poorer communities (Liu et al. 2022). The lives of all human beings, plants, and livestock systems are greatly influenced by climatic variability and climate changes as it disturbs food production at various levels starting from local, regional, to continental levels (Williams et al. 2020; Ahmed 2020). Life-threatening variability in maximum and minimum air temperature and precipitation patterns in all cropping systems influences the flora and fauna (Challinor et al. 2014; Hutchings et al. 2020). The thermal trend worldwide has become the chief ecological challenge in the present scenario, leading to enhanced mean air temperature in major cropping systems in an instance (Ali et al. 2019). Climate change in relation to agricultural production explained in two approaches is the direct impact of changing weather patterns which are caused by rising temperatures, heat waves, and changes in rainfall. This also includes increased atmospheric $CO_2$ levels: higher crop yields due to $CO_2$ fertilization but also reduced nutritional value of crops and indirect impacts from changed conditions include agricultural land loss from rise in sea level, less irrigation water availability, impacts on soil erosion and fertility, etc. (Gulati et al. 2009; Hoffmann 2011).

South Asia which is home to a quarter of the total world population covering about 3% of the world's land area is one of the important dryland agricultural regions in the world. The region is being struck particularly hard by climate change in the form of temperature rise. According to the World Bank, an increase between 1.5 and 3 °C (hotspot) by 2050 is expected for the average annual temperature of the region compared to 1981–2010, if nothing is done to reduce carbon emissions (Hoegh-Guldberg et al. 2018). This hotspot could lead to lower crop yield and a sharp decline in crop productivity, thereby putting in trouble almost 50% of the world's population (Ainsworth and Ort 2010). In order to reduce climate change, agricultural farming must incorporate sustainability (van Zonneveld et al. 2020) through building strong, resilient system by considering different factors (van Zonneveld et al. 2020). For the purpose of creating a logical framework for agricultural farming, interactive research of these components with farmers in mind are crucial. The majority of South Asian regions have seen temperature and rainfall variations that frequently resulted in heat waves, droughts, and floods that significantly harmed agriculture (Almazroui et al. 2020). India is the second most vulnerable to climate change amongst the Asia-Pacific region. The extremes in maximum and minimum temperatures are expected to increase with few places expecting more rain while some remain dry. India's agriculture is based on monsoon climate since time immemorial. In view of the fact that about 64 districts in India are rain areas, 42% of the food grain; 75% of oilseeds; 90% of dicot grams, sorghum, and peanuts; as well as 70% of cotton and more than 60% of rice fields of the total Indian agricultural production originate from dry and rainfed farming (Bhandari et al. 2007). Thus, dryland agriculture occupies nearly 75% of India's cultivated area and produces 44% of food requirements, from cereal grains to grain legumes to leafy vegetables, and a variety of arable crops are cultivated under dryland conditions. Also, root crops and some fruit vegetables are quite suitable for dryland farming. This means it will continue to play a critical role in India's food security, both now and in the future.

## 31.3 Challenges in Dryland Agriculture

Dryland farming crops are characterized by very low and highly variable and uncertain yields. Crop failures are quite common which are solely attributed by the following:

### 31.3.1 Inadequate and Uneven Distribution of Rainfall

In general, the rainfall is low and highly variable which results in uncertain crop yields. Besides its uncertainty, the distribution of rainfall during the crop period is uneven, receiving a high amount of rain when it is not needed and a lack of it when the crop needs it.

### 31.3.2 Late-Onset and Early Cessation of Rains

Due to late onset of monsoon, the sowing of crops is delayed resulting in poor yields. Sometimes the rain may cease very early in the season exposing the crop to drought during flowering and maturity stages which reduces the crop yields considerably.

### 31.3.3 Drought

Drought is a common phenomenon in the dryland agriculture. Crop productivity depends on the cumulative effects of water deficits on plant performance. Therefore, it is critical to understand the processes of water supply and demand in dryland crop communities and the role of adaptation in mitigating the detrimental effects of drought on crop yield. Drought stress along with high temperatures is now a recurrent event and has been intensified due to higher air temperature stress in most cropping systems (Högy et al. 2013). The effect of multiple abiotic stresses, e.g. a combination of high temperatures to drought on crops under field conditions, has been documented (Mittler 2006). The combination effect has more pronounced impact in comparison with a single stress on crops like barley and wheat (Shah and Paulsen 2003). The interaction effect has been reported to be seen in most parts of Europe (Rang et al. 2011) where the interaction resulted in reduced productivity of wheat and maize (Ciais et al. 2005). In Asia, drought along with high temperature stress was seen during the critical developmental stages of rice which resulted in major losses in the rice-based cropping systems (Wassmann et al. 2009). Cohen et al.

(2020) conducted a meta-analysis of drought stress along with high temperatures on crop yield and yield components. They inferred a significant decrease in crop yield which was due to the combined impact of drought and high temperature on harvest index, life cycle, seed number, seed size, and seed composition. Worldwide, it is found that at a higher temperature, the ultimate consequences of drought are amplified in comparison with lower air temperatures. The synergistic interactions between increased temperature and drought revealed that production was reduced more as a result of the combined stresses than by either stress alone and that a large portion of the influence was on physiological processes in crop plants in arid conditions (Amarasingha et al. 2015).

### 31.3.4 Prolonged Dry Spells during the Crop Period

Long breaks in the rainy season are an important feature of the Indian monsoon. These intervening dry spells when prolonged during a crop period reduce crop growth and yield and when unduly prolonged crops fail.

### 31.3.5 Low Moisture Retention Capacity

The crops raised on red soils and coarse-textured soil suffer due to lack of moisture whenever prolonged dry spells occur due to their low moisture holding capacity. Loss of rain occurs as runoff due to undulating and sloppy soils.

### 31.3.6 Low Fertility of Soils

Drylands are not only thirsty but also hungry. Extreme weather events are having a negative impact on the millions of fungi, billions of bacteria, and other microorganisms that live in soil. These microbes are crucial for the C and nitrogen cycling process; therefore, their lack or insufficiency might result in low soil fertility and productivity (Pugnaire et al. 2019). Long-term warming causing alterations in soil microbial communities has been documented (Cavicchioli et al. 2019). A 5 °C increase in temperature which shifted the ratio of bacteria to fungi causing variation in the respiration rate of the soil microbial community was reported (Bintanja 2018). Since temperature and respiration are correlated processes, current studies focused on how high temperatures affect microbial metabolism have been carried out (Gao et al. 2018). The primary factor in the decline of belowground biodiversity, which results in poor soil health, is intensive agricultural methods used in dryland farming systems. Given that climate change has both direct and indirect effects on soil communities, this loss will be more severe as a result of the changing climate (Dubey et al. 2019). Therefore, it has become mandatory to adopt sustainable management practices so that a healthy soil microbiome in dryland cropping systems can be promoted. Further, the key elements used to combat the perils of dryland agriculture are capturing and conservation of moisture, effective use of the available moisture, as well as soil conservation and control of input costs. On the other hand, there are also some challenges for dry farming in India. These include moisture stress and uncertain rainfall, effective storage of rainwater, and the selection of limited crops. Furthermore, proper disposal of dry farming products and the quality of the produce can be an issue.

## 31.4 Strategies to Mitigate the Effects of Climate Change on Dryland Agriculture

Climate extremes have a negative impact on agricultural production. If appropriate adaptation measures are not immediately done, this damage could result in problems with crop failure, lower agricultural yield, poor crop quality, and ultimately food insecurity at local, regional, and global levels. In order to lessen the harm that climatic fluctuation causes, adaptations are measures that are performed. Anticipatory adaptation or adaptation planning where measures are taken in advance to prevent adverse impacts has been recommended (Mimura et al. 2015). Instances include early warning system such as seasonal climate forecasts and disease forecasting, land use planning, crop yield forecasting, and management of water resources. In many production systems, reactive adaptation with a higher likelihood of keeping up with lower warming levels has been proposed (Travis et al. 2018). Plans for disaster risk management or systems for risk transfer that can be used to lessen or make up for risk effects are additional examples of adaptation (e.g. crop insurance and diversification). Given that both can contribute to lowering the vulnerabilities associated with climate change, adaptation and mitigation have strong linkages. Changes in technology and the addition of system alternatives that can lower resource inputs and emissions of greenhouse gases make adaptation and mitigation viable. Benefits from concomitant positive effects of climate change, e.g. [eCO2] and increased rainfall, are possible through adaptation strategies (Waha et al. 2013). These strategies include change in sowing date and appropriate choice of cropping systems and crops. Furthermore, adverse impacts of heat and drought stress could be moderated through adaptation measures. Farmers' perceptions have been analysed regarding climate change and explored connections between different stages of adaptation, i.e. perceptions, intention, and implementation (Abid et al. 2019). They worked on and stated that local understanding of climate change is a crucial consideration for the design incubation and adaptive measure implementations at the farm level. In addition, the study reported farmers' education as a vital precursor to implement the adaptive measures effectively (Ghose et al. 2021). However, factors that can improve farmers' adaptive behaviour to climate change include weather forecasting, market information, advisory services, and farming experience. Furthermore, large-scale farmers were able to adapt to climate change through change in planting dates and selection of new, adapted varieties. However, more attention was needed by small land holding farmers so that they can easily access information, institutional services, and resources to prosper in the fight against climate change. Further detail about possible prospects in managing dryland agriculture under climate change scenario encompasses diversification in the mixed and integrated crop and livestock farming system, introduction of legumes in the cropping system, genetic modifications of crops, change in crop management practices, conservation agriculture for sustainability in the cropping system, carbon sequestration, and different process-based modelling (including water and nutrient management, ideotype designing, modification in tillage practices, application of cover crops, and insect and disease management). Agricultural systems modelling is needed to enumerate the benefits and trade-offs from alternate practices at the farm scale. Modelling has played, and will continue to play, a substantial role in improving agriculture under different scenarios to feed the billions of people across the world (Rodriguez et al. 2014). By providing information about how the systems function and dynamically interact with biotic and abiotic components, models can aid in the design of resilient agricultural systems for dryland agriculture. These models can then instruct stakeholders on how to manage their specific system. The study of the impacts of climate variability and change on agricultural revenue of small-scale farmers in Kenya was done implementing the Ricardian approach (Ochieng et al. 2016). Results indicated that small farmers' livelihoods are significantly impacted by climate change and variability. Furthermore, their findings demonstrated that temperature is a much more significant signal than rainfall and called for the adoption of laws that would stop the depletion of natural resources. Crop insurance and integrated adaptation strategies, such as the adoption of drought-tolerant crop varieties, increased investment in agriculture, and the use of sustainable management techniques, should all be part of these policies (Ochieng et al. 2016; Sequeros et al. 2021). Statistical matching and econometric modelling were adopted for evaluation of how the climate-smart agriculture technologies and practices influence household income and asset accumulation of small-scale dryland farmers in Kenya (Ogada et al. 2020). The adoption of drought-tolerant crops combined with a commitment to livestock may be an effective adaptation strategy to lessen the effects of climatic variability and change, according to the results. Crop canopy-based trait adaptation techniques had also been proposed. There are agricultural techniques and measures developed specifically for farming under dry conditions. Adopting strategies including varied cropping systems, cover crops, crop residue absorption, little tillage, no tillage, balanced fertilization, and use of organic fertiliser could boost carbon sequestration in rainfed cropping systems (farmyard manure and green manure) (Newbold et al. 2015). In order to improve food security and reduce fossil fuel emissions (0.4–1.2 gigatons C per year), carbon sequestration has a significant deal of potential. Adding 1 tonne of carbon to degraded croplands might enhance crop yields by 20–40 kg $\text{ha}^{-1}$ for wheat, 10–20 kg $\text{ha}^{-1}$ for maize, and $0.5^{-1}$ kg $\text{ha}^{-1}$ for cowpeas (Lal 2004). For soil moisture conservation, deep tillage, surface tillage, and stubble use should be performed to optimize water movement and soil water penetration. With an eye to the sensible use of rainfall, surface water, and groundwater, proper watershed management can not only halt further deterioration of the ecosystem but also restore damaged soils. To increase the yields of crops, culture practices like mix cropping, intercropping, and crop rotation should be followed. Integrated pest management (IPM) techniques should be adopted to create unfavourable conditions for pests and weeds. In terms of effective utilization of water, it is recommended to use drip irrigation systems as well as practicing lining of canals. To develop these methods, non-farm operation dryland areas should be supplemented by other non-farm occupations such as animal husbandry, fisheries, poultry, and social forestry.

## 31.5 Future Perspectives

Future research needs to adjust its focus, in order to truly eradicate hunger. More than 475 million of the 570 million farms in the world are less than 2 hectares, according to an editorial in Nature, but most of our research has placed a higher priority on larger farms than on small farming. The majority of previous research has come to the incorrect conclusion that smallholder farmers can adapt to climate change by implementing new strategies, such as growing climate-resilient crops with the help of extension agencies.

## 31.6 Conclusion

Global warming and climate change are having a severe impact on all farming systems, but dryland farming systems are especially vulnerable. If we don't take appropriate mitigation measures, soil capabilities, yield and yield components, and resource usage efficiencies will all suffer irreversible losses. Therefore, technology-based intervention is required to support dryland agricultural methods in agriculture. Long-term sustainable development goals will be assisted by this support. The quantification of climate change's negative effects on dryland farming systems, the use of existing data sets with further analysis, and the implementation of "what-if" scenarios using process-based models can all help to reduce these effects. By using these methods, benefits and trade-offs under various sets of management practices can be evaluated over the short and long term in order to design strategies to lower risk in the face of extreme climatic conditions. The modification of the farming system structure, the introduction of legumes (microbial-based technologies), the improvement of varieties (water efficient or drought/heat tolerant), appropriate crop management techniques, intercropping, supplemental irrigation, conservation, erosion minimization and precision agriculture, carbon sequestration strategies, the adoption of agroforestry, and decisions for future needs could all benefit from this.

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# Adaptive Resilience: Sustaining Dryland Agriculture the Pastoralist Way

# 32

Aneet Kour, Varinder Singh Raina, D. K. Sadana, and Mihir Sarkar

## Abstract

Adaptive resilience of pastoralists is defined by their social, economic, cultural and ecological contributions in the face of environmental uncertainties and other vulnerabilities. Pastoral resilience in drylands is characterized by their mobility, diversity, flexibility and reciprocity which, in turn, effectively regulate pastoral socio-economics. The impending threat of climate change threatens to weaken the centuries-old pastoral production systems and their livelihoods. However, the inherent capabilities of these systems can be exploited to develop pastoralism-centric policies against climate change. Further, these resilient systems can be strengthened through certain short-term (like developing customized insurance products, early warning systems and credit access) and long-term (like improvement in basic infrastructure and services, acknowledging their ecological contribution through monetary and other means, land tenure rights to pastoralists and promotion of cross-border pastoralism) adaptation strategies for building a climate-friendly future. Effective pastoralism is the way forward for sustaining dryland ecosystems in changing climates.

## Keywords

Adaptive resilience · Pastoralism · Drylands · Climate change

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## 32.1 Introduction

‘Solitude is a chosen separation for refining your soul. Isolation is what you crave when you neglect the first’, quoted beautifully by Wayne Cordeiro, best paints the essence and existence of pastoralism. Pastoralism can be defined as human adaptability at its best with utter disregard for static food and shelter conditions and sheer courage in the face of natural calamities. It can be considered as the oldest and longest running living systems pursued by human civilization. Though it has been practiced to serve the economic needs of societies since time immemorial, the intangible benefits endowed by pastoralism in the form of biodiversity conservation and environmental sustainability are priceless.

Pastoral landscape can be described as the one harnessing the dynamic variability of the environments by means of strategic mobility and entrenched cultural values (Krätli et al. 2013). In a quest to subsist on the characteristic vulnerability of certain ecosystems marked by ephemeral nature of resources and climatic uncertainties, pastoralism entails movement based on the traditional ecological knowledge passed and refined over generations (Berkes et al. 2000; Tamou et al. 2018). Being in close association with their surroundings, pastoralists develop intricate mental maps of the flora and fauna adapted to specific environments which can be put to their advantage (Wario et al. 2015).

Though mobile livestock rearing by pastoralists is a form of economic adaptation, it is important not to undermine the adaptive capabilities and resilience of the nomadic pastoral communities. Pastoralists are probably the first victims to the ramifications of changing climate, and their critical resorts like grazing grounds and water sources seem to be directly threatened (Arjjumend 2018). However, time and again, they have developed local coping mechanisms and adaptive strategies suited to the changing environments.

Pastoral communities dwell in distinct climatic zones spread across mountain ranges and grasslands to the deserts, although dryland pastoralism is most prevalent (Behnke et al. 2013). Drylands constitute around 40% of the earth’s total surface based on low precipitation received by such areas. However, considering the dryland ecological features shared by alpine mountainous pastures, the area under drylands could be even higher. The defining characteristic of dryland pastoralism is endemic vulnerability coupled with economic subsistence and adaptive resilience (Herrero et al. 2016). It strengthens food security, provides economic livelihood and renders various ecosystem services.

Climate change is bound to spell doom for dryland ecosystems in the form of erratic rainfall patterns, excessive warming and land degradation (Huang et al. 2017), thus disturbing agricultural production, hampering food security and aggravating poverty in drylands. Pastoral communities have already been conditioned to face several challenges, climate change being one of them. Hence, dryland nomadic communities intrinsically equipped with time-tested coping strategies can offer potential lessons on adaptive pastoral strategies to withstand the vagaries of climate change (Davies and Nori 2008). Enhancing the adaptive capacity of these communities by addressing their concerns would be imperative for sustainable development of dryland agriculture.

## 32.2 Pastoralism in Drylands

Drylands are biomes shaped by water scarcity and encompass diverse ecosystems like grasslands, arid and semi-arid lands, savannahs, deserts, scrublands, etc. Given the extremely low precipitation in cold mountainous regions and polar zones, they may also fit into the criteria of drylands. Drylands can be found all around the planet and more extensively so in Africa where almost whole of the land mass of some countries is constituted by drylands. Drylands are one of the major contributors to the global agricultural economy (https://www.cbd.int/programmes/outreach/awareness/drylands.shtml). These are repositories of ecological biodiversity which, in itself, is an important risk mitigation strategy for those habitats (Davies et al. 2012).

Dryland ecosystems can be considered synonymous to adaptability as is reflected in their flora, fauna and pastoral lifestyle. Pastoralists in these regions are credited with developing some of the most unique crop varieties and livestock breeds through efficient adaptation strategies (Davies et al. 2012). In fact, pastoralism is considered as one of the most environmentally suited agricultural activity for dryland ecosystem (Steinfeld et al. 2006). Nomadic pastoral practice in Africa (where most of the agriculture is practiced in drylands) has been found to give higher returns than sedentary and enclosed systems at the cost of lower carbon footprint.

In a dryland setting, households deriving more than half of their income from nomadic livestock-related activities are arbitrarily deemed as pastoral, whereas those deriving more than half of their income from agricultural produce and around one-fourth from mobile livestock rearing are labelled as agro-pastoral. Further dissection of the pastoral production systems highlights that these can be differentiated into transhumant and nomadic based on their mobility patterns. Transhumant lifestyle regulates cyclical movement between relatively same locations during a particular time of the year (e.g. during summers and winters), whereas nomadic lifestyle involves greater uncertainties and irregularities in terms of movement and in search of ‘greener pastures’.

Mobility is one of the basic tenets of dryland pastoralism which facilitates economic utilization of sparse and otherwise inaccessible resources (Sharma et al. 2003). It is governed mainly by drawing information from multiple sources like historical experiences and traditional institutions and may sometimes involve movements across international borders as well (Semplici and Nori 2020). It promotes a flexible approach involving seasonal usage of pastures across different ecological zones effectively, creating economic value with almost zero input. Pastoral route is a trade-off between accessibility to forage and/or water resources, grazing period and energy expenditure during the journey which is subsequently influenced by altitudinal and latitudinal gradients (Frachetti et al. 2017; Turner and Schlecht 2019). Movement is also undertaken in response to factors like conflict, drought, new trading markets, emergence of newer resources, etc. Pastoral mobility is a multidimensional concept encompassing cultural interface, social organization and customary institutions besides livestock movement (Herrero et al. 2016; Turner and Schlecht 2019). All these components together make a perfect case for pastoral resistance in the face of untoward natural as well as manmade contingencies.

## 32.3 Pastoral Resilience

Resource management in dryland pastoralism is underpinned by characteristic mobility, diversity, flexibility and reciprocity, all of which contribute towards pastoral resilience (Fernandez-Gimenez and Le Febre 2010; Gillin 2021). Distortion in any of these features causes disturbance in pastoral socio-economics and aggravates the vulnerability of dryland ecosystem. The critical role played by these components in pastoral landscape is detailed below (Figs. 32.1, 32.2, 32.3, and 32.4):

### 32.3.1 Mobility

As discussed above, pastoral mobility is hinged on understanding of complex agro-ecological dynamics and access to resources. It provides an opportunity to utilize

**Fig. 32.1** Dryland pastoral landscape, Bhuj, Gujarat, India

**Fig. 32.2** Pastoral sheep flocks in drylands of Maharashtra

temporal and spatial differences in terms of vegetation on one hand and prevents overexploitation on the other. Therefore, it helps in preventing soil erosion by providing adequate time for revival and growth of grasslands (employing rest-rotation scheme) (Fernandez-Gimenez and Le Febre 2010). It also promotes and reinforces social ties which are vital for reciprocity (Swift et al. 1996).

### 32.3.2 Diversity

Harnessing diversity of livestock species is another weapon in pastoralists' toolkit for sustaining dryland ecosystems. This allows efficient utilization of the available scarce resources in drylands and maintains the stability of secondary production over time (Coppock et al. 1986). Maintaining herd diversity is a multipronged strategy which rests on the assumption that different livestock species have varying forage preferences and water requirements which can be successfully exploited to minimize competition and increase the carrying capacity of a region. Their livestock herd may be a cluster of various classes of livestock, viz. those who browse (e.g. goats), the ones who graze (e.g. cattle, sheep) and the generalists who can both graze as well as browse (e.g. camel). As far as the water requirements are concerned, camels traditionally accustomed to water shortages can be taken to greater distances for foraging,

**Fig. 32.3** Banni buffaloes moving towards jungle in late evening for grazing in Dhordo, Gujarat

**Fig. 32.4** Pastoral woman preparing for migration in Bhuj, Gujarat

whereas smaller ruminants like sheep and goat have a restricted access to grazing areas distant from a water source.

A diverse herd is also an insurance against natural calamities like heat waves, droughts, diseases and unprecedented snowfall due to differences in the coping abilities of different species, thus minimizing chances of a complete wipeout. In social terms, raising a mixed livestock herd comprising of different sizes and categories of animals promotes collective family labour as smaller stock can be tended by younger members of the family.

### 32.3.3 Flexibility

Flexibility can be safely interpreted in terms of mobility and diversity of the herd and can be manifested through practices like variation in movement patterns and herd splitting, etc. The optimum time and speed of movement is gauged based on the traditional ecological knowledge of the herders and, accordingly, is flexible and may vary in different years. For instance, transhumant yak herders in alpine mountainous regions start their downward migration based on the blooming pattern of particular flowers. Another common resilience tactic used by pastoral herders is seasonal or species-wise segregation of their herds into smaller groups. Herd splitting is usually done keeping physiological adaptation of the species and feeding selectivity in mind. In summers, camels are let out to graze at will, whereas other species like sheep and goat are kept in close surveillance. Yak herders also exhibit flexibility in splitting their herds between different altitudes based on their understanding of physiological capabilities of yaks (higher altitudes), yak-cattle hybrids (mid-altitude) and cattle (lower altitude). Social organization and groupings are also not rigid, and composition of households and herding camps may change on a seasonal or annual basis (Sylla 1995).

### 32.3.4 Reciprocity

Reciprocity finds echo in collective action and social denomination inherent in the pastoral societies. It finds expression in pastoral decisions underlying conservation, regulation and allocation of resources. Pastoralists often engage in reciprocal exchange and sharing of livestock (particularly bulls) as a nonmonetary support and to maintain herd variability. When it comes to pasture management, a social institution regulates pasture access and equitable benefits sharing. Transhumant herders practice flexibility in their movements to ensure that all the herders grazing in a specified area reach their destination on a designated date so that resources are equally available to livestock of all. Reciprocal pasture access to the neighbouring tribes or clans, exchange of labour and barter of livestock produce are performed as a mark of social support (Namgail et al. 2007; Postigo et al. 2008). Reciprocity is basically the backbone of social security and interdependence in pastoral societies which is more of a norm than an exception. It highlights strong ethical awareness and respect for social institutions in pastoral landscape and is, in fact, social capital accrued by these communities.

## 32.4 Impact of Climate Change in Drylands

Drylands sustain about half of the cultivated systems globally and provide direct or indirect support to one-fourth of the world population. Biodiversity is at the heart of these ecosystems with 32% of the global hotspots being native to the drylands. Of the entire land surface of earth, 40% is drylands, and in spite of the hardships, it provides shelter to a staggering 50% of the total livestock population. 30% of the total plant species are exclusively endemic to these areas. As far as the climate stewardship is concerned, world's drylands sequester around half of the global carbon emission in their soils (2010–2020: UN Decade for Deserts and the Fight against Desertification). Climate change is the most imminent threat for drylands with severe repercussions for life as well as production systems in these biomes. The impact of climate change in drylands can be assessed in terms of variability in climate patterns, vegetation and soil carbon content (Hanan et al. 2021).

### 32.4.1 Variability in Climatic Patterns

Climate trajectories may vary between drylands due to differing signals of climatic stress in tropics and polar regions, although rising temperatures, variability in rainfall patterns and increased incidences of extreme events like droughts, wildfires, floods, etc. would be a consistent feature in every region. Elevated temperatures will further deplete soil moisture in these areas, thus aggravating soil aridity. Increased aridity accompanied by greater frequency of dust aerosols (from natural and also the anthropogenic causes) will subsequently influence precipitation depending on atmospheric humidity, topography, geographical conditions, wind circulation and clouds (Huang et al. 2017). Global climate projections indicate that annual precipitation may show an upward trend in Eurasia and tropical parts of Africa and North America, whereas drylands in Australia, South America, North America, Southern Africa and Mediterranean countries should brace themselves for drier climates (Feng and Fu 2013).

### 32.4.2 Variability in Vegetation

Changing temperature and rainfall patterns would bring about changes in the vegetative landscape of drylands. Increases in the atmospheric $CO_2$ concentrations accompanied by changing weather regimes will necessitate changes in the pasture composition and its quality. The net productivity of the drylands will be determined by a complex interplay between rising greenhouse gas emissions ($CO_2$ in particular), higher temperatures and widely fluctuating precipitation. $C_3$ herbage species (cool-season plants) stand to benefit in areas with warmer climate frequented by increasing rainfall, whereas $C_4$ grasses will dominate in parched and drier landscapes (Hatfield et al. 2011). The most deteriorating impact would be witnessed in the forage quality due to faster senescence of plant tissues (Dumont et al. 2014). Climate change will be a double-whammy for livestock as heat stress will accelerate cellular lignifications in forages, thus decreasing dry matter digestibility on one hand (Lu 1989) and resulting in thermoregulation-induced lesser voluntary intakes (Beatty 2008) on the other. Another impending threat of climate change is vulnerability of native flora and fauna to the attack from invasive and alien species which will increasingly dominate the habitats.

### 32.4.3 Variability in Soil Carbon Content

Drylands could be safely considered as planet's carbon sinks as they sequester four times higher carbon content in their soils than terrestrial biota and three times higher than the atmospheric carbon content. Climate change will further expose the drylands to the perils of degradation and increasing desertification as the organic carbon storage capabilities of dryland soils will decrease with the rising temperatures. Intense rainfall events will also reduce soil carbon intake by preventing moisture infiltration and reducing plant growth (Fu et al. 2021).

## 32.5 Pastoralism Vis-à-Vis Climate Change

The relationship between pastoral systems and climate change is double-edged, viz. worsening effect of climate change on pastoral systems and opportunities presented by drylands to shoulder climate responsibility.

Changing climate has negatively impacted pastoral livelihoods through recurrent floods, droughts, pasture shortages and frequent outbreaks of livestock diseases (Ahmad and Afzal 2021). Increasing sedentarization amongst pastoralists in Uganda (Wurzinger et al. 2009), severe droughts in African Sahel region (Epule et al. 2014), Australian rangelands witnessing heat waves (Litchfield 2020), increased severity of livestock diseases in Pakistan (Ahmad and Afzal 2021), cattle starvation and deaths in Tanzania (Kimaro et al. 2018) and greater work burden for pastoral women in India due to gendered division of labour (Venkatasubramanian and Ramnarain 2018) are some of the stories of climate wrath on the pastoral communities. Pastoral critics also point out that low efficiency of pastoral production causes these systems to have higher carbon footprint (and hence, climate impact) for every kg of milk or meat produced than semi-intensive or intensive systems of production.

However, the strengths of pastoral production systems vis-à-vis globally stressed food production systems in the wake of climate change are worth mentioning. Dryland pastoralism has substantially lower water footprint than intensive livestock farming due to its extensive nature and non-dependence on the water-guzzling fodder crops, as is the case with the latter. Also, pastoral livestock production poses no serious competition to humans in terms of edible feed as witnessed in intensive and semi-intensive systems, thus contributing immensely to food security in the world. Another critical contribution of dryland pastoralism to the fight against climate change is its natural role as a potential sink of carbon and greenhouse gases. Having vast expanse and being far from saturation in terms of carbon losses, drylands can serve as a bridge in addressing the burgeoning issues of carbon sequestration and land degradation. Hence, pastoralists driving the dominant production system in drylands can be one of the major stakeholders on the climate table.

Estimates indicate that 36% of the global carbon is stored in drylands and it shoots up to 60% in case of Africa (Campbell et al. 2008). If properly managed, it is possible to sequester around one billion tonnes of carbon per year in the dryland soils (Lal 2004). Long-term experimental studies on soil organic carbon content in different production systems also concluded that pastoral livestock production systems in drylands had highest reserves of soil organic carbon (Maillard and Angers 2014). However, increased desertification has caused severe onslaught on soil carbon reserves in drylands which needs to be addressed. Appropriate afforestation practices (with suitable species), restoration of ecosystems and soil and pasture management can help in re-sequestration of about two-thirds of the historic carbon losses (about 1 Petagram of soil organic carbon per year) (Lal 2004). Maintaining the ecological integrity of drylands and promoting climate-resilient pastoralist practices would be instrumental in achieving Sustainable Development Goals particularly Goal 1, No Poverty; Goal 2, Zero Hunger; Goal 10, Reduced Inequalities; Goal 11, Sustainable Cities and Communities; Goal 12, Responsible Consumption and Production; Goal 13, Climate Action; Goal 15, Life on Land; and Goal 17, Partnerships for the Goals. Recognizing and acknowledging the indispensable role played by pastoral people in sustainable management of grazing lands, poverty alleviation, nutritional security and safeguarding ecosystems, the United Nations has recently declared 2026 as the International Year of Rangelands and Pastoralists (IYRP) (https://www.iyrp.info/). IYRP 2026 also integrates and complements the efforts of the initiatives like UN Decade of Family Farming 2019–2028 and UN Decade on Ecosystem Restoration 2021–2030, all of which are crucial for a sustainable future.

## 32.6 Strengthening Pastoral Resilience

Pastoralism seems to be at the crossroads in the light of recent developments. Pastoralists do not accord such high importance to climate change and consider it just one amongst many threats including restrictions on mobility posed by change in land use, lack of access to resources, nonavailability of basic infrastructure and healthcare facilities, livestock-wildlife conflicts and adversarial governance policies. Therefore, future deliberations should focus on coherently integrating climate agenda with the measures directed at mitigating pastoral threats. Enabling the adaptive capacities of these self-sustaining systems by implementing short-term and long-term adaptation strategies would strengthen pastoral resilience in the face of climate change.

## 32.6.1 Short-Term Adaptation Strategies

### 32.6.1.1 Insurance Products

In order to enable effective pastoralism in variable climates, there is an immediate need to introduce diversified pastoral dryland-specific insurance products like weather index-based livestock insurance and transport risk insurance (Amare et al. 2019). This can provide buffer through the climate uncertainties particularly droughts and incessant rains and can even cover more specified risks like changes in the average rainfall and vegetative production patterns, etc. Hence, pastoralists can hedge themselves and their livelihoods against even minor changes in the thresholds of climate parameters in their particular areas. For instance, if the mean rainfall is lower than its usual average for the area, herder will receive an indemnity.

### 32.6.1.2 Early Warning Systems

Extreme weather events like desertification, drought, floods, etc. mostly catch nomadic herders unawares and put pastoral systems under tremendous stress. Therefore, early warning systems (EWS) can caution the herders beforehand regarding the treacherous climate trajectories. They can develop their own contingency plan for, say, impending drought conditions in their summer grazing grounds or low water table en route their migration. Dissemination of critical information through EWS will make pastoralists proactive and will enhance their resilience. In Kenya, a decision support system has been established for early warning of dryland pastoralists that combines three components, viz. water balance, phytomass growth and spatial analysis combined in a model to forecast forage growth for the upcoming 6 months (Matere et al. 2020).

### 32.6.1.3 Customized Credit Availability

Credit access has always been a major challenge for dryland pastoralists and must be improvised to pastoral advantage. Preconditions like permanent address proof, traceability and other collaterals hinder the pastoral herders from approaching the banks for credit and put them into the trap of moneylenders. Research points out that improving the mechanisms of credit access can lead to sustainable livelihoods and asset development in pastoral drylands (Mekuyie et al. 2018).

## 32.6.2 Long-Term Adaptation Strategies

### 32.6.2.1 Availability of Basic Infrastructure and Services

Improved infrastructure, education and healthcare are critical for overall development of pastoralism. Nearby local markets and proper road infrastructure for migration and product sale will significantly improve pastoral livelihoods, thereby enhancing their participation and reducing the costs (Nassef et al. 2009). This will also give them a sense of market understanding so as to make better informed decisions. A landmark example of the significance of market access for reviving pastoral economy is the case of *Maldhari* community of Gujarat, India, who got organized (*Banni Pashu Uchherak Maldhari Sangathan*) with the help of a local NGO and entered the dairy market of Gujarat. Today, their economy stands at several hundred crores, and they have been actively voicing for greater rights over their rangelands (https://banni.in/). African initiatives like Policy Framework for Pastoralism in Africa (Addis Ababa 2010) and Common Market for Eastern and Southern Africa (https://www.comesa.int/) also aim to provide market opportunities and enhanced market access for the dryland nomads.

Education is another important factor from the standpoint of pastoral rejuvenation and will further equip these communities in the fight against climate change. Pastoralists already realize this and sometimes split families in order to allow one or two younger members to stay back and educate themselves while the rest of the household practices mobility. Being a fundamental right almost globally, education should be made widely accessible to each and every individual in the pastoral groups. However, the traditional bricks-and-mortar classrooms would be to the detriment of pastoral mobility and resilience. Hence, radio along with other modes like mobile school, distance learning, etc. could be a viable option. A special 'pastoral curriculum' should be drafted and taught focusing on the knowledge needs of these communities on one hand and promoting pride and respect in their lifestyle on the other (https://dlci-hoa.org/assets/upload/education-documents/20200804021843179.pdf). Also, two-way interaction in pastoral education needs to be encouraged so that the knowledge and lessons on adaptation are shared by the pastoralists with the outside world.

Healthcare interventions such as livestock treatment and vaccination camps at particular spots en route pastoral movement, veterinary helplines dedicated to pastoral issues and decentralized healthcare system suited to pastoral needs (Duba et al. 2001) could be incorporated in the district wise plan to ensure inclusive healthcare for pastoral population. Also, dryland healthcare system should have 'One Health' as its focal strategy (Gammino et al. 2020; Wild et al. 2020), that is, convergence and integration of human as well as veterinary health objectives and related interventions and outreach activities aimed at providing joint coverage with community engagement and participation.

#### 32.6.2.2 Acknowledging Ecological Contribution

In order to contribute towards ecosystem-based adaptation in pastoral landscapes, rehabilitation of watersheds, agroforestry, conservation agriculture, eco-tourism and pastoral tourism should be promoted as means to climate adaptation.

Another interesting prospect could be payment and rewarding pastoral communities for soil carbon sequestration and biodiversity conservation through specific mechanisms. The concept of 'Payments for Ecosystem Services (PES)' entails monetary or nonmonetary compensation to pastoralists conditioned on fulfilment of an ecosystem service (Pappagallo 2018). The twin objectives of PES schemes are to protect the ecosystem and, more importantly, to induce behavioural changes. Probably, the first success story of PES framework was Wildlife Conservation Lease Programme under which a contract was signed between an NGO, the Wildlife Foundation and landowners of Maasai community in Kenya. Under this agreement, landowners were made to allow free movement of wildlife in their lands (adjacent to Nairobi National Park) in return for Ksh 300 per acre. The amount was deduced based on complete calculation of the average income levels of each household from the sale of milk, dung and skin per month. As a result of this PES scheme, all the intended targets including increasing conserved area and indicator species population, reducing pastoral vulnerability to drought, gender empowerment and creating environmental awareness were almost fully achieved (https://www.omicsonline.org/open-access/the-kitengela-nairobi-national-park-wildlife-conservation-lease-program-2157-7625.1000146.pdf). Another such example is the RAPCA (Red de Áreas Pasto-Cortafuegos de Andalucia) scheme in Spain which was designed to counter wildfires in forest ecosystems. It involves local shepherds as the service providers who practice targeted grazing of their flocks to maintain low biomass levels in the identified fuel break areas in forests. Shepherds are paid an initial bonus amount of 300 euros followed by 42 to 90 euros/ha based on difficulty in grazing. The payment amount is also contingent on accomplishment levels, and less than 50% of the compliance does not attract any remuneration (Varela et al. 2018). Besides cash remuneration, nonmonetary returns like interest, altruism, reputation, self-image and other prosocial concerns may also be banked upon for delivery of ecosystem services (Kaczan et al. 2017; Abildtrup et al. 2021).

Also, dryland pastoralists could be introduced to the clean development mechanisms and carbon financing markets so that they can reap benefits in return for their ecosystem services.

#### 32.6.2.3 Governance and Land Tenure Rights

One of the major hindrances to pastoral development is the neglect of their rights by governments. This attitude usually stems from a viewpoint that pastoralism is an archaic and non-efficient production system and needs to be ‘replaced’ with better production systems. Land tenure and access rights bestowed by customary pastoral institutions are not considered as legally binding, thus promoting private investment in productive dryland patches under the garb of development. This puts the traditional grazing areas for pastoral herds under threat and is a major issue for sustenance of pastoralism. Therefore, attempts at reconciliation between statutory and customary laws should be directed at bringing pastoral communities to the dialogue table for drafting policies, coordinating and integrating different scattered efforts for pastoral development and strengthening pastoral institutions and civil society working for them (Food and Agriculture Organization of the United Nations 2018). Decentralization and inclusive governance is vital for making ground-level changes in a participatory manner. Local institutions play vital roles in their understanding of key issues and problems, providing intended services, championing pastoral rights and effective decision-making (https://www.iied.org/mapping-innovative-governance-for-sustainable-development). PLI or Pastoralist Livelihoods Initiative in

Ethiopia is directed at strengthening grassroots democracy by strengthening local pastoral institutions.

As pastoralists have their own community norms and rules to regulate efficient resource use in drylands, some countries have formulated national policies considering land titles for these communities. Majority of the African countries have a customary system of land tenure. In the Philippines, the constitution accords statutory land rights to indigenous communities, while Indonesian law stipulates the incorporation of customary institutions and rules in national land laws (Kasimbazi 2017).

Registration and integration of pastoral seasonal land rights into the statutory law (https://landportal.org/sites/default/files/lengoiboni1.pdf) and common resource management with continued mobility and flexibility (https://landportal.org/node/71197) seem to be other interesting propositions.

#### 32.6.2.4 Regional Dimensions of Pastoralism

The grazing lands of pastoralists usually cut across national boundaries providing them with the opportunities to engage in resource management, livestock genetic improvement, social exchanges and trade between the bordering nations. However, they are often on the losing end on both sides of the border and suffer the heat of interstate conflicts and violence. The never-ending conflicts in Sahel and West African region are classical examples of this (https://unowas.unmissions.org/sites/default/files/rapport_pastoralisme_eng-april_2019_-_online.pdf).

A regional approach to developing pastoralism needs to be fostered amongst the neighbouring countries for sustained ecosystem benefits on both sides. This can include cross-border initiatives on animal health to curb transboundary diseases, regional trade in pastoral produce, peace and goodwill efforts and infrastructure building for joint development. COMESA for common trade market and ECOWAS for facilitating cross-border movement of transhumant pastoralists (https://www.unhcr.org/49e479c811.pdf) are innovative approaches pursued in Africa to address cross-border issues and to evolve common sustainable solutions.

The regional dimension of pastoralism can only be realized once there is an acknowledgement of economic, social, cultural and environmental contribution of pastoralists within the countries.

## 32.7 Conclusions

Traditionally, pastoralism and drylands have been ignored and labelled as unproductive due to their perceived lower contribution to the global growth. However, these systems have been sustaining worldwide growth in the form of indispensable ecosystem services and planet responsibilities. Pastoral drylands can be best described as climatic vulnerability combined with environmental instability and entrenched cultural values. Therefore, adaptive resilience is intrinsic to pastoralism and makes it one of the most compatible systems of production in drylands. Time-tested pastoral coping strategies help them to mitigate changing climates, thus making it one of the myriad other threats faced by these communities. However, it is touted to become a grave danger for the dryland ecosystems as the global warming continues at an unprecedented rate. Hence, enhancing the adaptive capacities of pastoralists by incorporating climate adaptability measures in the developmental framework for drylands is the way forward. Focus must be directed at enabling and strengthening the autonomous adaptation of these pastoral communities. *Since centuries, pastoralists have been supporting the planet at the cost of their own suffering. Now, it's time to pay them back.*

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# Part VII

# Farm Mechanization in Dryland Agriculture

# Resource Conserving Mechanization Technologies for Dryland Agriculture

# 33

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## Abstract

The continuous deterioration in natural resources and climate change has put enormous challenges before researchers to further improve the crop productivity to meet the food grains demand of the burgeoning population from existing even reduced land resources. The faster depletion of groundwater, soil health deterioration, and change in rainfall patterns are key issues being faced in every agro-ecological zone of the country. Such problems are more prominent in dryland agriculture due to the limited moisture regime during the crop growth period. The unnecessary delay in the field operation, seeding at improper depth, mismanagement of crop residue, and inadequate water-conserving techniques lead to poor germination, resulting in lesser yield and profitability. In this book chapter, resource conserving mechanization technologies for different field operations ranging from seedbed preparation to threshing of crops in dryland agriculture are discussed. Under the favourable moisture regime, a shift from conventional tillage to resource conserving tillage practices, viz. zero and strip tillage either on flat or broad bed, would be helpful to reduce the fuel cost, operational time, and associated harmful air pollutants along with increased net profit for farmers. The use of such resource conserving technologies along with crop residue as mulch and subsurface drip irrigation system will provide the double benefits of energy and water conservation. The high losses and low input use efficiency in chemical and fertilizer applications are associated not only with increased cultivation cost but also with their harmful impacts on soil, water, and air. Researchers and

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farming communities are encouraged to use frontier technologies such as electrostatic sprayer, drones, etc., to reduce the losses and optimal application of chemical and fertilizers. In crops, especially row crops, integrated weed management practice involving both chemical and mechanical control needs to be adopted due to the evolution of herbicide resistance in several weeds upon solely relying on chemical control. The farmers belonging to small landholding and engaged in cereal-based cropping systems can make scale-based appropriate choices to use power tiller for tillage/tillage + sowing, self-propelled reaper for harvesting, and multi-crop thresher for threshing of such crops in an economical manner.

**Keywords**

Crop residue · Conservation agriculture · Farm implement · Tillage · Precision planter · Energy · Drip irrigation

## 33.1 Introduction

Mechanization has played an imperative role in improving the cropping intensity and achieving the surplus food grains production from existing land resources in addition to timeliness in field operations with reduced drudgery. The farm power availability has been continuously increasing and achieved a value of 2.02 kW $ha^{-1}$ during 2013–2014 against 0.28 kW $ha^{-1}$ during 1960–1961 (Fig. 33.1). The food grains productivity also followed the rising trend with time due to high yielding

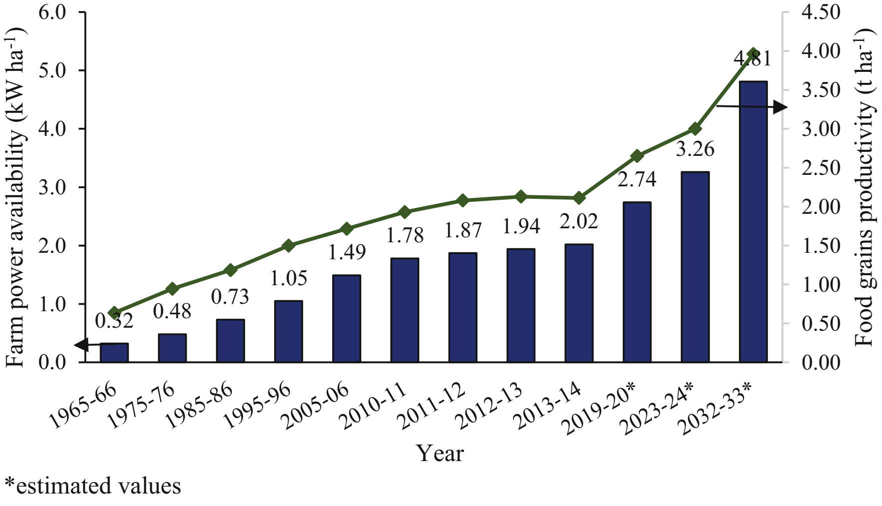

**Fig. 33.1** Year-wise trend of farm power availability and food grains productivity [data source: Singh 2015, GoI 2015, NITI Aayog Report 2018]. *estimated values

**Table 33.1** Classification of dryland area based on aridity index

| Common name | | Area (million km$^2$) | Percent of the total land area[a] |
|---|---|---|---|
| Desert | Hyperarid | 9.8 | 6.58 |
| Semi-desert | Arid | 15.7 | 10.54 |
| Grassland | Semiarid | 22.6 | 15.17 |
| Rangelands | Dry subhumid | 12.8 | 8.59 |
| Total | | 60.9 | 40.89 |

Source: United Nations (2020)

[a] Calculated from the total land area of 148.94 million km$^2$

cultivars, better irrigation facilities, and mechanized farming. Considering the primacy of mechanization, the government of India (GoI) has set the milestone to achieve 4 kW ha$^{-1}$ power availability by 2030 (NABARD 2018). In the last few decades, a drastic change has been observed in the utilization of different power sources, and in recent times, a major demand of farm power is fulfilled in the form of mechanical power. It is expected that mechanical power will increase to 82%, leaving the share of animate power just to 4.1% by 20232-33 (NITI Aayog Report 2018). However, the status of farm power availability and mechanization level varies in different regions, cropping systems, and even in different field operations. Punjab and Haryana states are resource (land and farm power availability) rich, while states like Uttar Pradesh, Bihar, Odisha, Uttarakhand, Himachal Pradesh, etc., have limited resources. Similarly, crops like rice and wheat under irrigated conditions have more mechanization levels than crops like cotton, millet, etc., grown in the dryland regions.

Dryland covers about 40.9% of the total land area and supports more than 2.1 billion population worldwide (United Nations 2020). In India, the dryland area is about 80 million hectares (mha), and it contributes about 44% of the total food grains production in the country (Anonymous 2021). Dryland areas have precipitation constraints and have an aridity index (ratio of mean annual precipitation and mean annual potential evapotranspiration) below 0.65. Dryland areas are further divided into dry subhumid, semiarid, arid, and hyperarid zones as given in Table 33.1. Dryland agriculture needs special attention on improving mechanization, soil and water-conserving techniques, and other resource conserving technologies to improve the productivity of crops grown in such conditions amidst climate change scenarios. The adoption of mechanized farming in dryland areas would be helpful to improve the cropping intensity in addition to enhanced crop productivity and reduced input cost. In this book chapter, resource conserving technologies having applications in various field operations ranging from seedbed preparation to harvest and threshing of crops grown in dryland agriculture are discussed.

## 33.2 Resource Conserving Technologies for Tillage, Seed Bed Preparation, and Sowing Operations

### 33.2.1 Chisel Plough

The periodic rainfall and then long dry spell in arid and semiarid zones make soil hard and create an impervious layer, which needs to be shattered using suitable tools. Chisel plough is a curved bar type common tool used for breaking the hardpan of the subsurface layer to facilitate the water infiltration into the soil. It loosens and aerates the soil without soil inversion while keeping the crop residue on the soil surface like in zero-till practice and reduces the soil erosion. This implement can be used for deep ploughing up to 45–75 cm depth. The intermittent chisel ploughing improves root development as a result of improved soil structure and enhances drought tolerance of crops. The use of chisel ploughing in dryland areas improves soil moisture regime as well as crop yield. The implement is useful for dryland areas suitable for cultivation of roots, tubers, and other crops. Mohanty et al. (2007) found 20–28% lesser soil penetration resistance, 60% higher root length density, 21.4% increased water use efficiency, and 20% more grain yield of rainfed soybean with conventional tillage + subsoiling with chisel plough at 35 ± 5 cm depth over conventional tillage (twice tillage of topsoil by sweep cultivator). Wang et al. (2020) also reported 4% higher uptake of nitrogen, 6–8% more grain yield of wheat along with 7.4% lesser N losses, and 39.7% reduction in $N_2O$ emission with chisel plough tillage over conventional plough tillage in dryland winter wheat-summer maize cropping system in China.

### 33.2.2 Subsoiler

Subsoiler works at greater depth than conventional tillage implements to break the compacted soil layers formed due to repeated use of heavy machinery or as a result of ploughing at a constant depth. It is heavier than a chisel plough and used for penetrating the soil at 60–90 cm depth. Subsoiler is operated by high-power category tractor (>60 hp) due to its high draft requirement. So, generally, 20° lift angle (angle of tool face from horizontal) is provided in a large subsoiler to reduce the draft as a result of upward shear force exerted by the tool. Moreover, curved standard/shank requires comparatively lesser draft force over the straight shank. The positive effects of subsoiling on soil water storage and grain yield of crops in dryland agriculture are well documented (Martínez et al. 2011; Cid et al. 2014). Cid et al. (2014) recorded 14.7–19.7% higher yield of maize under maize-cotton cropping system with intermittent subsoiling in permanent bed over maize yield on permanent bed. Liu et al. (2016) found 23.5–29.1% higher grain yield and 5.8–8.5% increase in water use efficiency of spring maize with subsoiling (every or alternate year) at 50 cm depth over conventional tillage. Shukla et al. (2017) also reported 19.7% higher cane yield with subsoiling at 45–50 cm over conventional tillage. In rainfed or dryland agriculture, conservation or minimum tillage should be adopted rather than inversion tillage to improve the soil water storage by utilizing the crop residue on the soil surface (Lampurlanés et al. 2016).

### 33.2.3 Blade Harrow

Blade harrow (either animal or tractor operated) is a popular secondary tillage (minimum or zero-soil inversion) implement, which is widely used for preparing the seedbed in clayey and black soils in central India. It consists of one or more (straight or V shape) blades attached to a beam, which cuts the thin slice of soil along with weeds and leaves it without any soil inversion. The application of the implement is also extended to intercultural operation in row crops such as maize, cotton, sorghum, etc., and soil mulching to conserve the soil moisture. Blade harrow provides reasonably good weeding efficiency (60–65%) in row crops (Thyagaraj 2008). Pathak et al. (2013) found 15.9–19.2% increase in sorghum yield and 14–16% reduction in soil loss with one additional inter-row tillage by blade harrow over normal intercultural treatment during the low to medium rainfall years.

### 33.2.4 Laser Land Leveller

Laser land leveller is a modern resource conservation technology, which has made a remarkable contribution in conserving irrigation water. Generally, agricultural fields are levelled by traditional methods, which leave some areas of the field with high elevation, causing these regions to suffer from water stress condition, while some areas of field having low elevation undergo surplus water conditions. It causes variability in water and nutrients applied to crops, resulting in uneven crop stand and yield. These problems can be addressed by laser land leveller, which comprises scrapper, hydraulic system, transmitter, receiver, and control box as main components (Fig. 33.2). It removes the soil from area having higher elevation and fills it in the area of lower elevation, thereby precisely levelling the field within ±2 cm of mean elevation of the field. Precision land levelling improves water distribution efficiency, water productivity, and crop yield. The adoption of laser land levelling helps in reducing water, nutrient, and energy inputs in dryland agriculture in addition to improving crop productivity and profitability (Shahani et al. 2016). The study conducted in the Raichur district of Karnataka state indicated that the adoption of laser land levelling can increase rice yield by 5 q $ha^{-1}$ and net income by Rs. 5000 per annum (Pal et al. 2020). Miao et al. (2021) found water distribution uniformity of 77–91%, water use fraction 75–88%, and water productivity up to 2.7 kg $m^{-3}$ of surface irrigated maize crop grown on laser levelled field. Chen et al. (2022) reported 23.2% increase in yield of winter wheat along with 30–40% increase in net return through an integrated approach of precision land levelling + precision seeding over conventional farmers' practice. Amidst climate change and declining resources, the adoption of laser land levelling would be beneficial to farmers to reduce the input costs and improve net profitability.

**Fig. 33.2** Use of laser land leveller at farmers' field

### 33.2.5 Duck Foot/Sweep Cultivator

It is a tractor mounted implement that consists of a rectangular frame made of steel, rigid tynes, sweep blades, and a three-point mounting system. The sweeps of the implement are triangular in shape like the foot of a duck and attached to tynes with fasteners. The sweeps of the implement can be replaced once these are worn out. During the field operation with the duck foot cultivator, the depth of cut is controlled by the hydraulic system of the tractor. The implement is widely used for surface cultivation and intercultural operation in heavy soils and provides the advantage of soil moisture conservation. In a long-term study, Sommer et al. (2011) found 2.7 g $kg^{-1}$ increase in soil organic matter of topsoil (0–20 cm) with shallow tillage by duck foot cultivator across all residue management treatments over conventional tillage in barley-vetch and barley-vetch/wheat-vetch crop rotation in dryland agriculture. Somasundaram et al. (2018) found higher water-soluble aggregates and aggregate-associated carbon with reduced tillage by duck foot cultivator over conventional tillage practice in soya bean-pigeon pea, soya bean-wheat, maize-pigeon pea, and maize-chickpea cropping systems in rainfed vertisols of India.

### 33.2.6 Mulcher

It is a tractor PTO (power take-off) operated implement used for shredding/chopping of crops residue (Fig. 33.3). The power is transmitted from the PTO shaft to gearbox of the implement and then to the crushing drum through V-belt drive. The blades ('Y'-shaped blade with or without straight and hammer blades) mounted on crushing drum rotate at high speed and cut the crop residue into small pieces. The smaller size

**Fig. 33.3** Use of mulcher for shredding of paddy straw

of straw formed after mulching operation also facilitates its faster decomposition and sowing operation with a spatial seed drill. Direct seeding of crops can be performed on chopped straw to conserve the soil moisture and to realize other benefits on soil health and net profitability. Verma et al. (2016) performed field tests on tractor-operated paddy straw mulcher and found an effective field capacity of 0.32 ha ha$^{-1}$, fuel consumption of 5.66 L h$^{-1}$, and 83.4% straw chopped with less than 10 cm size. The wheat grain yield (41.83 q ha$^{-1}$) with treatment having paddy straw mulcher + spatial drill was at par but with a 23.6% lesser cost than conventional tillage practice. In a different study, Kumar et al. (2018) reported 0.35–0.37 ha h$^{-1}$ field capacity, 79.5–81.0 field efficiency, 12.5–14.7 L ha$^{-1}$ fuel consumption, and 82.5–84.9% cut of stubbles with similar-sized rotary mulcher of two different makes. The field operation with mulcher after harvesting of crop provides preliminary helps in realizing the multifarious benefits associated with direct seeding of the crop with spatial drill under residue covered field.

### 33.2.7 Strip-Till Drill

Strip-till drill is a tractor's PTO-operated implement for direct seeding of various crops. The front part of the implement is similar to rotavator except for the type of blades with an additional sowing attachment at the rear of the machine. It is comprised of 'J'-type blades, which provide tillage in narrow strips required for proper seed-soil contact and better germination of crops rather than complete coverage of soil as in case of super seeder or conventional tillage. Strip-till drill is an intermediate option between conventional and zero tillage and provides the advantage of improved seed germination as with normal tillage operation in direct seeding of crops without complete coverage of soil. Sainju et al. (2006) recommended the use of conservation tillage (strip or zero tillage) with vetch/rye cover crop for an optimized yield of cotton and sorghum crops and N uptake along with reduced soil erosion and N leaching losses. Similarly, Gangwar et al. (2006) recorded a higher mean yield of wheat with reduced (strip) tillage over conventional and zero tillage options in rice-wheat cropping system under sandy loam soil. Jaskulska et al. (2018) reported higher plant density and more uniform growth of rapeseed plants with strip tillage technology over conventional tillage under the conditions of diverse textured soils and unfavourable distribution of rainfall. Thapa et al. (2019) found 5–6 °C lower soil temperature, 2.3–3.9% higher soil moisture conservation, and 15.2% more soil organic carbon in conservation tillage (strip tillage and zero tillage) based on corn-sorghum cropping system under dryland agriculture over conventional tillage practice. The reduced tillage and crop diversification were recommended as beneficial option for dryland agroecosystem.

### 33.2.8 Turbo Happy Seeder

The turbo happy seeder (THS) is basically the upgraded version of the happy seeder with the ability to work well even in heavy straw conditions with less energy demand. In THS, the cutting and shredding of straw are accomplished with inverted ‘γ’-type flails fitted on a rotor (1000–1300 rev $\text{min}^{-1}$) inside the straw management drum. The flails shear the standing stubbles near the ground and also smash the residue against serrated blades fitted on the interior walls of the drum to achieve the fine chopping and shredding (Fig. 33.4). The flails sweep past each sowing tyne twice per rotation, allowing the tynes to clearly pass through the straw. The THS also produces far less dust and leaves the sowing rows exposed compared to previous prototypes (Humphreys and Roth 2008; Saunders et al. 2012; Sidhu et al. 2015). Sidhu et al. (2015) reported improved yield of wheat sown into paddy stubble fields with the turbo happy seeder as compared to the conventional practice of straw burning followed by tillage and sowing operations. The use of THS also decreased fuel expenditure and ensured the optimum sowing window along with reduction in the irrigation requirement. Singh et al. (2020) reported higher weed infestation in wheat crop sown with conventional method as compared to zero tillage and turbo happy seeder. The poor germination with zero tillage sowing as compared to sowing with THS and conventional method was observed.

**Fig. 33.4** Turbo happy seeder used for direct seeding of wheat under loose rice residue

### 33.2.9 Seeder/Planter Cum Herbicide Applicator

Timely control of weeds is essential for achieving the desired level of yield. Herbicide application is generally the most popular method adopted to overcome this problem. The use of pre-emergence herbicides is an essential part of conservative farming, as it helps to control the weeds in early stage of crop and maximizes the productivity which further eliminates the application of post-emergence herbicide. The combined seeder/planter cum herbicide applicators help to perform the sowing and weed management functions simultaneously. Walia et al. (2009) reported improved yields of 61.7% and 42.1% in the direct dry-seeded rice following the pre-emergence application of pendimethalin @0.75 kg $ha^{-1}$ with a post-emergence application of bispyribac @25 g $ha^{-1}$ or azimsulfuron @20 g $ha^{-1}$, respectively, compared to an alone application of pendimethalin @0.75 kg $ha^{-1}$. Reddy et al. (2015) reported a saving of 21.87 man-h $ha^{-1}$ in groundnut sowing under rainfed conditions with a planter cum herbicide sprayer as compared to sowing with a manually operated seed drill followed by the use of a power-operated knapsack sprayer for herbicide spraying. The implement had a field coverage rate of 0.47 ha $h^{-1}$ and an herbicide application rate of 1100 litres $ha^{-1}$. The cost of the conventional method of sowing and herbicide spraying was observed to be 27% higher than the planter cum boom sprayer. Samreen et al. (2017) developed and evaluated a multi-crop roto drill cum herbicide applicator having an integrated rotavator, seed hopper (trough feed type), and a rocker sprayer pump. The machine was simultaneously able to perform the tillage, sowing, and herbicide applications in one pass. It was reported that the total time needed to cover a one-hectare field with developed machine was 3.68 h, i.e. 26% lower as compared to the total time required for carrying out individual operations.

### 33.2.10 Pneumatic Precision Planter

A pneumatic-type seed metering mechanism gives high precision in seed placement with minimal seed damage, precise depth control, and good uniformity in intra-row plant spacings and is suitable for a wide range of seed types (Parish et al. 1991; Zhan et al. 2010). This type of planter has the capability of metering the nonuniform seeds, apart from the spherical ones. Currently, the availability of skilled labours is gradually decreasing, resulting in an increased cost of cultivation. The sowing operation of cotton crop requires high labour demand (15%) next to its harvesting (44%) (Vaiyapuri 2004). These planters work on the suction principle (Fig. 33.5). Air is sucked through a rotating plate with equidistant holes placed radially. Any seed coming in contact gets stuck to the holes on the plate and fell immediately when suction is cut off at the lowest position near the ground. The fall of the seed is synchronized with the predetermined seed spacing. Thus, the exact planting of a single seed is obtained. However, it requires high-quality seeds for better performance. Kathirvel et al. (2005) reported 42.9 and 96.3% saving in cost and time, respectively, for sowing of the cotton crop with a pneumatic planter in comparison

**Fig. 33.5** Use of pneumatic precision planter in the field

with the traditional method. Mandal et al. (2018) designed a vacuum metering device for a power tiller-operated precision planter. The rotational velocity of the seed metering disc as 0.11 m $s^{-1}$ and a vacuum pressure of 6 kPa were reported to be suitable for the precise metering of soybean, pigeon pea, and corn seeds. Verma et al. (2018) reported saving of Rs. 1274 per hectare or 49% with a tractor-operated pneumatic planter in comparison with manual broadcasting of sunflower seeds. Khambalkar et al. (2014a) assessed the utility of a self-propelled pneumatic planter in dryland conditions for sowing crops such as sunflower, sesamum, soybean, etc., and reported 50 to 67% saving in cost of operation as compared to the traditional method of sowing. The expenses on seeds were reduced up to Rs. 1350 $ha^{-1}$ in the case of cotton and Rs. 1000 $ha^{-1}$ in the case of sunflower.

### 33.2.11 Multi-Crop Raised Bed Planter/Broad Bed Furrow (BBF) Planter

The crop productivity under rainfed farming is usually less due to the deficit of available soil moisture. Therefore, it is imperative to embrace appropriate machinery to conserve the rain water in situ to warrant sufficient moisture during different growth stages of the crop. Broad bed furrow cultivation has several benefits for saving in water application, mechanical weeding, placement of fertilizers, moisture conservation, reduced lodging, and good plant stand (Astatke et al. 2002; Srinivas 2005). The broad bed furrow planters/raised bed planters help in carrying out the simultaneous preparation of broad bed furrows and sowing operations (Fig. 33.6). Ridgers or bed shapers perform the function of conveying and shifting the loose soil on top of the bed. Fahong et al. (2004) reported better grain quality and yield (>10%), improved nitrogen use efficiency (30%), saving of irrigation water (30%), and reduced operational costs in raised bed system as compared to flat sowing in wheat crop. Kumar et al. (2013) conducted feasibility trials of a tractor-operated raised bed planter for wheat. The planter was suitable for making two beds with 675 mm base width, 350 mm top width, and slanting height of 200 mm. The mean depth of placing seeds was 41 mm. The planter covered 0.28 ha $h^{-1}$ with field efficiency of 71–73% when operated at a working velocity of 2.27 km $h^{-1}$ with a 35 hp tractor. Khambalkar et al. (2014b) conducted feasibility trials of a broad bed furrow planter for chickpea, safflower, and onion crops under dryland conditions. The higher moisture conservation, increase yield, and lower energy requirement were observed with bed furrow planter than the conventional practice of sowing.

**Fig. 33.6** Picture illustrating the field operation of multi-crop raised bed planter

## 33.3 Resource Conserving Technologies in Fertilizer and Chemical Applications

### 33.3.1 Ultrasonic Orchard Sprayer

Spraying in orchards with traditional fixed-rate sprayers often results in either over-spraying or under-spraying as trees are spaced at a regular distance within the rows with great diversity in canopy size and density (Salyani et al. 2007). Wastage of chemical inputs and environmental degradation are serious issues with traditional techniques of pesticide application in agricultural and horticultural crop production. Traditional aero-blast sprayers apply pesticides continuously between trees resulting in the loss of a significant portion of applied chemicals, thereby causing environmental pollution and financial loss to the farmers (Derksen et al. 2007; Chen et al. 2013). The variable rate technology (VRT) is crucial for the precise use of inputs. The VRT spraying system basically has a crop scanning unit, a micro-controller unit, and a spray delivery system with electro-hydraulic or proportional solenoid valves. Ultrasonic or laser sensors could be convincingly utilized for the precise characterization of crop canopy. An ultrasonic canopy sensor-based sprayer delivers pesticide only when it senses the trees canopy which allows chemical savings up to 30–80% as compared to traditional fixed-rate sprayers (Wandkar et al. 2018). In ultrasonic sprayers, with the information on crop rows spacing, the present location of the machine, and operating speed, the desired spray volume is determined, and the nozzle output discharge is modulated accordingly. Solanelles et al. (2006) evaluated an ultrasonic air-assisted sprayer that could regulate the pesticide application rate in proportion to the measured width of the tree canopy. In this study, 70, 28, and 39% reduction in liquid usage was observed in olive, pear, and apple orchards, respectively, than the conventional spraying method.

### 33.3.2 Electrostatic Sprayer

The conventional spraying techniques have drawbacks of high spray discharge, low pesticides deposition efficiency, and higher drift, resulting in pollution of the ecosystem and health threats to humans (Ru et al. 2008; Xiongkui et al. 2011). In India, the key reason for a lower yield in cotton, maize, sorghum, millet, and oilseed crops is the poor control of insects and pests. According to Dhaliwal et al. (2010), the maximum loss in cotton amounts to 18.0–50.0% followed by crops such as sorghum and millets (3.5–30.0%), maize (5.0–25.0%), and oilseeds (5.0–25.0%). Farmers generally spray diluted pesticides with a conventional backpack sprayer having the hydraulic nozzles. However, the spray distribution is poor with more labour cost. The air-assisted sprayers produce smaller droplet sizes, but due to lack of control, lots of chemicals (about 90%) get wasted due to drift (Pimentel and Levitan 1986). Electrostatic sprayer functions based on Coulomb’s law with the primary objective of charging spray chemical to increase the percentage deposition on plant surfaces. Electrostatic sprayers work effectively on dense and broad leafy crops such as cotton, soya bean, etc. (Singh et al. 2013). The charged chemical droplets are attracted by the leaf surfaces having an opposite charge which reduces the drift and minimizes the wastage. The charged droplets move upward and underside of the leaf surface. There are three methods of charging pesticides, i.e. induction charging (5–15 kV), ionized charging (30–70 kV), and direct or conduction charging (25–30 kV) with induction charging as the most widely used charging method for an electrostatic sprayer (Matthews 1989; Singh et al. 2013). The high voltage is obtained using a solid-state electronic generator. Patel et al. (2016) in a comparative study found that the droplet density by an electrostatic sprayer in the cotton crop was 47–78% higher than that of tractor-operated gun sprayer, powered backpack sprayer, and lever-operated backpack sprayer. Also, 26–59% higher average bio-efficacy along with 44–62% less volume of spray liquid was observed using the electrostatic sprayer. In the present scenario, the limitations of this technology in Indian agriculture include its high initial cost, less mobility of the system under field conditions due to advanced electrical system required for charging the spray, and lack of awareness among the farmers.

### 33.3.3 Unmanned Aerial Vehicles (UAV)/Drones

The conventional spraying techniques result in extra pesticide doses, nonuniform spray, and environmental contamination (Hafeez et al. 2022). Further, the conventional methods of pesticides/fertilizer spray need more time and are less effective (Mrema et al. 2014). Unmanned aerial vehicles or drones (Fig. 33.7) are emerging as a countermeasure for the continuously decreasing agricultural labour population. These can be used to spray pesticides as per the spatial variability of the crops and level of the extremity of the pest attack with huge potential in locations with tough access for tractors. The spraying of chemicals over tall crops can be done easily by drones without any damage. The pesticide injection system includes a tank, flight controller, diaphragm pump, brushless direct current (BLDC) motors, spray boom, and nozzles. The downward airflow attributes of the propeller blades, speed, discharge, pressure, number of nozzles, nozzle type, and its location affect the efficiency of pest control. Spraying for weed, insect-pest and disease management, spreading micro-granular pesticides, and fertilizers are among the diversified applications now being recognized for UAVs (Pathak et al. 2020). However, in the present scenario, the price of UAVs, low carrier volume, and shortage of skilled pilots are specific hindrances in its market growth.

### 33.3.4 Tractor-Operated High Clearance Boom Sprayer

Mechanized spraying in most of the row crops including cotton is not possible after a certain crop height. The tractor-operated high clearance boom sprayers facilitate the easy movement of the machine in the standing crop even at the late stage with

**Fig. 33.7** Picture illustrating the spraying application with drone in the cotton crop

**Fig. 33.8** Use of tractor-operated high clearance boom sprayer in maize crop

minimum injury or damage to the crop (Fig. 33.8). This type of sprayer has a prime mover, chassis with high ground clearance, liquid tank with the agitating unit, sprayer pump, strainers, control valves, relief valves, pressure gauge, and a boom with various nozzles (Singh 2016). The boom height is adjustable to accommodate the various crops, and the boom is foldable for ease in transportation. Generally, the front-drive wheels are narrower, while the rear wheels serve the purpose of steering. Fenders are also given to divert the branches away from the front-drive wheels for minimizing the crop damage. Mechanical or jet agitation technique is used for proper mixing of chemicals and water in the tank. The large boom (up to 12 m length) allows higher effective field capacity in the range of 1.6–2.0 ha $h^{-1}$. It can be operated up to a working speed of 5 km $h^{-1}$. The chassis design of the self-propelled high clearance sprayer is very crucial because the drive system, frame, steering system, and suspension system of the chassis affect the operator's comfort in riding, manoeuvrability, stability, and protection (Gao et al. 2014; Chen et al. 2020). Apart from that, the self-propelled or tractor-operated air sleeve boom sprayers prove to be much advantageous in tall field crops such as cotton in which the pests such as whiteflies, aphids, and thrips attack the underside of the leaves and mostly at the time of boll formation (Singh et al. 2010; Yasin 2012). With the help of air sleeve boom sprayers, the air inside the crop canopy is completely replaced with spray-laden air using a blower which increases the effectiveness of the applied chemical as compared to the conventional boom sprayer, aero blast sprayer, and mist sprayer (Singh 2016).

## 33.4 Water-Conserving Technologies

### 33.4.1 Drip Irrigation System

In the dryland regions of Indian subcontinents, a few farmers are following subsistence farming due to overreliance on natural rainfall. Micro-irrigation systems are extensively recognized as the most successful technique of irrigation with greater water use efficiency and water productivity and less conveyance and distribution losses (Keller and Bliesner 1990; Kumar et al. 2015). In India, the gross area under micro-irrigation is 10.3 Mha, while there is a huge potential of 69.5 Mha under micro-irrigation (Jain et al. 2019). Rajasthan contributes a maximum 17.9% of the gross area under micro-irrigation followed by Andhra Pradesh (15.5%) and Maharashtra (15.1%). There is also the possibility of more area coming under irrigation due to the saving in water achieved through embracing the drip system (Fig. 33.9). Research carried out in the Indian subcontinent revealed an increase in yield between 20 and 50% for cotton, sugarcane, grapes, and tomato crops. According to Ashoka et al. (2015), with the adoption of a drip irrigation system, approximately 44, 37, and 29% can be conserved for sugarcane, grapes, and banana crops, respectively. Chandrakanth et al. (2013) witnessed 64.8% increase in net returns and 321.5% increase in the marginal productivity of water with the use of a drip irrigation system in comparison with the traditional system in the dryland

**Fig. 33.9** Surface drip irrigation system used in the wheat crop

regions of Karnataka, India. According to Shashidhara et al. (2007), dryland farmers reported reduced water consumption of 95% and cost saving of 92% (irrigation labour), along with even distribution of water and better quality of the areca nut and banana produce using a drip irrigation system. Palaniappan et al. (2009) reported 61–73.8% water saving along with higher yields of tomato and chilli crop using a low-priced drip irrigation method compared to the surface irrigation method in dryland alfisols in Tamil Nadu. Kumar and Palanisami (2010) in an economic study conducted in Tamil Nadu state found that the drip method can save about 71% of charges incurred in weeding compared with flood irrigation with significant improvement in the yield of coconut, grapes, and banana crops.

### 33.4.2 Subsurface Drip Irrigation System

In subsurface drip irrigation, water is applied to a significant region of the plant root zone with application rates of a similar amount to a surface drip system while sustaining a comparatively dry soil surface. Inline drippers are laid under the soil surface to conserve water, hamper weed growth, reduce nutrient and chemical leaching, and keep down run-off with additional benefits of protecting the system against any harm by animals and implements during the intercultural operations. The crops irrigated through subsurface drip irrigation generally give more yields compared to surface drip irrigation as it reduces the evaporation from the ground surface (Michelle 2005; Singh et al. 2006). A carefully installed subsurface drip irrigation system can last for about 10 years. Singh and Rajput (2007) reported an increase in okra crop height, yield (11.56–13.48%), and water use efficiency with laying down the laterals at 0.10–0.15 m below the soil surface. Kadbhane and Manekar (2021) recommended subsurface irrigation with plastic bottles as the most economically viable option to achieve the higher productivity with the minimum usage of water based on the cost-benefit analysis conducted on 3-year data of the grape crop at Nashik, India. Babiker et al. (2021) obtained approximately 30% higher maize yield with 95% less water consumption in the drylands of Sudan having subsurface irrigation system as compared to the surface irrigation system.

### 33.4.3 Sprinkler Irrigation System

Sprinkler systems increase the water use efficiency for dense crops where providing water independently to each root is not suitable with the help of drip irrigation. These systems try to imitate the rain in the manner that the run-off and percolation losses should be minimum. Efficient water application techniques such as drip and sprinkler irrigation can significantly improve the crop yield in the dryland regions when combined with water harvesting and storage in farm ponds (Murty and Jha 2011; Srinivasarao et al. 2014). The sprinkler irrigation system is generally suitable for field crops (e.g. wheat, groundnut, sorghum, etc.), row crops, and trees for applying water under or over the canopy (Shankar et al. 2015). Flowers and vegetable crops are usually not irrigated with sprinkler system due to their fragility (Kumar et al. 2009). Kumari et al. (2018) reported 21.37% increase in the yield of wheat crop and 43.86% increase in benefit-cost ratio with 33.21% water saving under sprinkler irrigation system as compared with conventional surface irrigation. Kumar and Choudhury (2022) observed 55% water saving with 25% reduction in the wastage of fertilizer using an IoT-based sprinkler system in the wheat crop. Several researchers observed an increase in crop yield (5–50%) with reduced water application (10–40%) and more water productivity (10–50%) with sprinkler system in comparison with traditional surface flooding (Dhawan 2002; Gupta et al. 2022). Currently, the government is providing about 50–100% subsidy to the farmers to install the sprinkler irrigation system based on the landholding area, as the initial cost of the system is very high (Mane and Ayare 2007; Shankar et al. 2015).

### 33.4.4 Plastic Mulch Laying Machine

Mulching is a strategy to help in conserving the moisture of soil in water deficit circumstances, suppress weed population, moderate soil temperature, and offer micro-climate to the crop (Veer et al. 2017; Iqbal et al. 2020). A plastic mulch laying machine is shown in Fig. 33.10. No-till with plastic mulch is a suitable tillage practice for the sustainable intensification of wheat production in semiarid areas (Peng et al. 2019). The plastic mulch colour might also affect the crop yield. According to Anikwe et al. (2007), tilled black plastic-film mulched treatment had the highest corn yield of 29.1–31.0 Mg ha$^{-1}$ followed by tilled clear plastic-film mulched treatment with corn yield of 20.0 Mg ha$^{-1}$, whereas no-till, no mulch plots

**Fig. 33.10** Field operation of plastic mulch laying machine

had corn yield of 7.9–8.2 Mg $ha^{-1}$. The black-coloured plastic mulch is usually employed which helps to obstruct the sunrays and hamper the weed growth surrounding the crop (Lamont 2017; Marihonnappanavara et al. 2018). Kadbhane and Manekar (2021) found drip-irrigated plastic mulching as the best technique for the grape crop to achieve higher yield (35–40%), water productivity, and biomass in comparison with the drip irrigation system. Daryanto et al. (2017) revealed that plastic mulching on ridges along with channelling rainwater into narrow furrows results in significant improvement in wheat and maize crop yields as compared to irrigated crops in the drylands with 24% less water requirement. This was due to much greater water use efficiency and better retention of water. However, in the present scenario, the expense of plastic mulch laying and disposal problems inhibit its widespread adoption, despite its encouraging results in the dryland regions.

### 33.4.5 Conservation Agriculture

Conservation agriculture is generally referred as the practice of minimizing soil manipulation, covering soil surface with residue or cover crop, and following better crop rotations for improving crop the productivity. According to Kumar et al. (2011), by embracing different long-term conservation agriculture practices in arid and semiarid regions of the Indian subcontinent, farmers can earn an additional net benefit varying from Rs 325 to 18,000 $ha^{-1}$ (based on the prices for the year 2010). The results revealed that conservation agriculture not only helps to improve the soil health but also further provides greater net return/unit farm area. Blaise et al. (2005) reported notably greater net returns in the cotton-pigeon pea strip intercropping system in the rainfed areas of central India by following the conservation tillage along with residue mulching and integrated nutrient management practice. Improved cotton lint yields can be obtained with green manure legumes as an intercrop and adopting the conservation tillage practices (Daniel et al. 1999; Varco et al. 1999). Venkateswarlu et al. (2007) observed that in the rainfed alfisols in southern India, legume cover crop in the sorghum-sunflower cropping system helped in getting significantly higher grain yield in addition to improved soil organic ‘C’ and microbial biomass. For promoting the conservation of agricultural practices across dryland regions, proper policies and institutional and technical support are required.

## 33.5 Effective Technologies for Mechanical Control of Weeds

The effective control of weeds should be from integrated weed management strategies rather than relying solely on chemical control methods due to their negative impact on the environment as well as product quality. Mechanical weed control is an alternate and successful weed management strategy especially in row crops, organic agriculture, orchards, and vegetables. Mechanical controlling of weeds especially in vegetables eliminates the risk of the residual effect of a chemical on the product as in the case of chemical control methods. In certain conditions, the mechanical weed control method can outperform other methods (Hussain et al. 2018). Some commonly used mechanical weed control methods are discussed below.

### 33.5.1 Narrow Tyne/Interrow Cultivator/Interrow Weeder

Narrow tyne or interrow cultivator is a tractor or power tiller-operated implement which has dragging type narrow shovels (30–40 mm) or sweep blades or powered individual cutting unit with ‘J’ or other type of blades for each row of the crop. The shovels or blades of the implement have smaller width as compared to the wide width of shovels and ‘L’-shaped blades (60–80 mm) of normal cultivator and rotavator, respectively, used for secondary tillage operation. The narrow width of shovel or blades enables it to use for mechanical weeding in crops with wide as well as small row spacing with reduced damage to the crop during the intercultural operation. A tractor-operated interrow weeder is presented in Fig. 33.11. The initial and subsequent flush of weeds, when crop height is not tall, can be controlled by a narrow tyne cultivator. The use of narrow-width tyres in the tractor during such intercultural operations reduces crop damage and improves the field capacity of the implement. Mohler et al. (1997) used various mechanical measures (rotary hoe, tine weeder, shovel cultivator, rotary cultivator-spiders, rolling cultivator-disks, in-row

**Fig. 33.11** Use of tractor-operated interrow weeder for mechanical weeding in cotton crop

cultivator with spyders and torsion weeders/spring hoes, in-row cultivator with spyders and spinners, in-row cultivator with spyders, spinners and torsion weeders/spring hoes) to control the weeds in corn crop and observed 39–74% reduction in weed density and mean crop damage of 6% by cultivation with a rotary hoe or tine weeder. The control of weeds established from roots, rhizomes, and tubers was better by cultivation over the chemical approach. However, the mean net return was higher in the case of chemical control of weeds. Martelloni et al. (2016) used interrow cultivator to control the weeds in dry bean crop and found 40% decline in weed density over control treatment. In a different study, Alba et al. (2020) reported the combination of rotary hoe for early weed control and interrow cultivation before canopy closure as an effective measure for greatest weed control and higher yield of lentil under organic conditions. The findings of above-cited studies suggest the potential applicability of narrow tyne/interrow cultivator for controlling the weeds in row and leguminous crops grown in dryland agriculture.

### 33.5.2 Spring Tyne Harrow

Spring tyne harrow is also known as flexible tyne harrow, spike tooth harrow, spring tooth harrow, and drag harrow. It consists of pegs-shaped teeth of a diamond cross-section mounted on a tooth bar. Spring tyne harrow is widely used for whole crop cultivation in European countries for controlling the weeds in organic culture-based small grain cereals and seed legumes (Rueda-Ayala et al. 2010). It is also used for breaking the crust layer of the soil, stirring the soil, and covering the seeds with soil. Spring tyne harrow controls the weeds by uprooting the small weeds and soil burying. The effectiveness in weed control increases with the aggressiveness of harrow, but it also increases crop damage. Therefore aggressiveness of the harrow or weed covering effect is adjusted by changing the forward speed, depth of operation, and number of passes to have optimum selectivity (ratio of percent of weed control and crop soil cover). Harrowing in dry soil conditions provides better weed control. Zeng et al. (2021) performed soil bin and field tests on the weeding performance of spring tyne harrow at different operational speeds (4–10 km $h^{-1}$), spring loadings (low, medium, and high), and weeding timings (early, mid, and late). The loading setting of the spring at high provided increased weeding efficacy (74–78%) over the other two settings. The middle weeding timing (20–22 days after sowing) favoured the least crop damage and reduced final weed density in the wheat crop. The mechanical control of weeds in various row crops cultivated in dryland areas using spring tyne harrow could provide better weed control efficacy as well as soil aeration, substituting the chemical approach at least on a partial scale.

### 33.5.3 Intra-Row Weeder

The recent advances in sensors and vision technology enable us to control intra-row weeds by mechanical means. The plant-to-plant spacing, speed of operation, the accuracy of plant detection module, response time, etc., strongly affect weed control efficacy and crop damage. Kumar et al. (2020) developed a prototype of an electronically controlled four-bar linkage mechanism connected to the vertical rotary weed control unit and found increased damage of plants at higher forward speeds and lower plant spacing. The preliminary field evaluation of the developed prototype showed weed control efficacy of more than 65% and plant damage less than 25%. Chandel et al. (2021) developed an integrated weeder having 'V'-shaped sweep for interrow and 'J'-shaped spring tynes controlled by a hydraulic motor for intra-row weeding in row crops. In the optimum range of intra-row tyne rotary speed to forward ratio (0.8–1.3) with a forward speed in 0.50–0.56 m $s^{-1}$ range, weed control efficacy of 92.8 and 84.1% was observed in maize and pigeon pea crop, respectively, along with plant damage within 6% and field capacity of 0.22–0.26 ha $h^{-1}$. In a different study, Jia et al. (2021) developed an infrared beam-based spirally moving sliding-cutting bevel tool for intra-row weeding in maize crops. The mean weeding efficacy of 95.8% and plant damage of 0.6% was realized upon conducting the tests on the developed tool with 800–1400 rpm of bevel tool, the forward speed of 4–7 km $h^{-1}$, and depth of operation as 2–14 cm. It is evident from the literature that electronically controlled different mechanisms based on intra-row weeding tools have been developed in recent times and tested in various row crops. It requires more research and development to improve the weeding efficacy of intra-row tools with minimal crop damage, increase working operational speed, and extend such tools in crops having a lesser row-to-row and plan- to-plant spacing.

### 33.5.4 Self-Propelled Power Weeder

Self-propelled power weeder, also known as a mini weeder, is a multipurpose implement used for seedbed preparation as well as for weeding operation in vegetables and row crops by small landholding farmers. It is an important tool for mechanization in hilly regions, where landholdings are marginal and large implements and tractors cannot be operated. The implement is usually equipped with a petrol engine, which transmits the power to the rear cutting unit having 'hoe' or 'C' or other types of blades. The turning of the power weeder is done by means of a dog clutch provided on both sides of the handle. Srinivas et al. (2010) evaluated the performance of a power weeder with three different blades ('L', 'C', and sweep) in sweet sorghum crop and reported higher weeding efficiency (91%) and increased performance index (169.8) along with lesser cost of operation (Rs. 429 per hectare) with 'L'-type blade over other two blades. Dixit et al. (2011) conducted field tests on performance evaluation of rotary power weeder of two makes with 'L' and 'L-C' blades in cotton crop and reported 94–95% weeding efficiency, 1–3% plant damage, 0.11–0.13 ha $h^{-1}$ field capacity and 50–60% saving in cost over manual weeding operation. Tewari et al. (2014) performed field experiments on performance evaluation of rotary power weeder in tomato, yard long bean, and okra crops and found weeding efficiency of 96–97%, effective field capacity as 0.08–0.096 ha $h^{-1}$, and plant damage of 1.6–2.8%. It can be understood that the self-propelled power weeder extends its applicability from seedbed preparation to mechanical weed control in vegetables and row crops and is a multipurpose useful tool for small farms.

Mechanical control of weeds is an alternative to chemical control and is considered an important pillar of integrated nutrient weed management approach. The advances in vision and automation technology provide a distinguishment between crop and weed and weed control in both interrow and intra-row. However, lower efficacy of weed control in intra-row, higher capital cost, dependency of effectiveness on the soil and weather conditions, and higher operational time and cost are the major reasons for the slow adoption of mechanical weed control method.

## 33.6 Resource Conserving Technologies for Harvesting and Threshing Operations

### 33.6.1 Self-Propelled Reaper

Self-propelled reapers harvest the crops almost from the ground surface. It consists of an engine, power transmission system, crop-row divider, star wheels, cutter bar assembly, feeding, and conveying devices. Based on their operational and function components, it may be vertical/horizontal/bunch conveying type, or reaper binder. The vertical conveyor reaper may be riding type, walk-behind type, or tractor mounted. The crop after being cut is dropped in a windrow on the side. The working width usually varies from 1.20 to 2.20 m. The field capacity of the machine generally ranges from 0.25 to 0.40 ha $h^{-1}$ (Gajakos et al. 2013; Murumkar et al. 2014). For harvesting the cereal crops such as wheat and paddy, pulses such as Bengal gram, and oilseed crops such as rapeseed, mustard, soybean, and safflower in dryland agriculture, vertical conveyer reapers are very useful having much better field capacity and field efficiency than manual harvesting of these crops (Alam et al. 2018; Nadeem et al. 2015). Gajakos et al. (2013) reported 38.63% saving in the cost of operation and 67.81% saving in time requirement with a vertical conveyor reaper than the manual harvest of the soybean crop.

### 33.6.2 Cotton Stalk Shredder

In India, around 46 million tonnes (Mt) of excess cotton residue is produced each year with most of the stalk being considered an agricultural waste despite its utility as fuel by rural people (Hiloidhari et al. 2014). Cotton stalks contain about 67.3–70% hemicellulose, 24.3–28.2% lignin, and 5.9–8.3% ash and are also rich in nutrients such as C, H, N, K, P, Ca, S, Mg, Fe, Mn, Zn, etc. (Dubey et al. 2004). Burning of cotton stalks causes loss of available valuable nutrients. One of the difficulties in cotton production is the need to clear crop residues after harvesting. Conventionally, the stalks are either manually pulled or cut with a sickle from 50 to 75 mm above ground and burnt consequently. The manual eradication of cotton stalks is very strenuous and consumes more time. A tractor-operated single-row cotton shredder is

**Fig. 33.12** Tractor-operated single row cotton shredder

depicted in Fig. 33.12. Sutaria et al. (2011) observed that the recycling of cotton stalks in dryland conditions by chopping into small pieces of 50–60 mm using the cotton shredder with the addition of compost culture resulted in enriched compost with higher content of all plant nutrients in less than 120 days. Ahmad et al. (2020) developed a cotton stalk puller shredder to help in eradicating the pink bollworm host in the cotton crop. The machine was able to shred the cotton stalks into small sections varying in length from 51 to 76 mm for easy soil incorporation. Vora et al. (2020) conducted experiments under dry farming conditions in cotton crop and observed that the ex-situ composting of stalks using the shredder gave the highest yield compared to other management practices, i.e. removal, in situ burning, and soil incorporation using rotavator and mobile chopper. Senthilkumar and Thilagam (2015) used a tractor front-mounted cotton shredder and a rear-mounted rotavator for in situ shredding and mixing of stalks in the soil. A favourable increase in hydraulic conductivity, decrease in bulk density, and increase in N, P, K, and organic ‘C’ of the soil were observed.

### 33.6.3 Multi-Crop Thresher

Multi-crop threshers are more popular among farmers for threshing various cereals and pulses and are suitable for dryland crops. The major benefits of these threshers over mono-crop thresher are that these can thresh a number of crops using a single thresher with some minor adjustments. It can be operated using a stationary engine, electric motor, or tractor for threshing of wheat, soybean, sorghum, paddy, etc. The threshing efficiency of multi-crop thresher varies between 98 and 99% and cleaning efficiency between 97 and 99% (Karthik and Satishkumar 2015; Pandey and Stevens

2016; Kumari et al. 2020). The separation of grain from earhead is done by impact of the crop on threshing cylinder and rubbing of the crop between the threshing cylinder and concave. Oscillating sieves and blowers are provided for separating and cleaning the grains from the chaff. These threshers can be useful for threshing the different crops such as wheat, gram, barley, mustard, pea, etc., by minor adjustments and using alternate sieves. Pandey and Stevens (2016) evaluated the performance of a multi-crop thresher for gram crop and reported an output capacity of 9.62 q $h^{-1}$ at a cylinder speed of 600 rpm along with a net saving of 31% as compared to the conventional manual threshing method. Kumari et al. (2020) developed a multi-crop thresher having output capacity of 34, 75, 58, 54, and 30 kg $h^{-1}$ for wheat, paddy, barnyard millet, finger millet, and amaranth, respectively. The threshing and cleaning efficiency for these crops greater than or equal to 98% and 95%, respectively, were reported.

## 33.7 Conclusion

Dryland agriculture plays a vital role in fulfilling the food grains demand of the burgeoning population of India. The declining natural resources joined with the adverse impacts of climate change such as shift in rainfall pattern, frequent drought events, etc., have put the enormous pressure on dryland regions. Moreover, dryland regions had been lagging in mechanization and manmade resources due to inadequate importance given to dryland crops. In this book chapter, emerging mechanization technologies in various field operations are discussed in the context of dryland agriculture. A shift in the crop production system from conventional tillage to non-inversion tillage (chisel ploughing, subsoiling, blade harrowing), reduced tillage, and zero tillage under residue mulch conditions would provide twin benefits of soil moisture and energy conservation, leading to improved germination and higher yield of crops with reduced input cost and lessened harmful impact on the environment. The adoption of precision levelling and planting equipment in dryland crops can reduce the cultivation cost and improve input use efficiency by properly utilizing the seed and fertilizer. Advanced spraying technologies such as drones, electrostatic, and high clearance boom spraying need to be adopted for optimal usage of chemicals with reduced losses and their harmful impact. The adoption of micro-irrigation techniques (surface and subsurface drip irrigation, sprinkler irrigation) and mulch-based cultivation (residue or biodegradable plastic) of vegetables and cereal crops would be beneficial to improve the water use efficiency and conserve water resources. The integrated weed management approach involving mechanical control of weeds should be adopted to overcome the evolution of herbicide resistance in various weeds. The mechanization in harvesting and threshing of dryland crops especially barley, oats, rye, sorghum, millets, etc., needs more attention to reduce the losses, operational time, and drudgery in these operations. Future research focussing on the mechanization of dryland crops is desirable to diversify the cropping systems and to further improve the contribution of dryland agriculture in food grains production and the economy of the country.

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# 34

# Agricultural Mechanization for Efficient Utilization of Input Resources to Improve Crop Production in Arid Region

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## Abstract

Around 12% of India's geographical land is classified under arid soil where traditional rainfed farming predominates in most parts of these arid soils. It is very important to find or develop suitable techniques for agricultural mechanization in this area. In some areas of the country like Punjab and Haryana, mechanization has been increasingly fine-tuned and widely advocated by several farmers, thus enhancing the way of agricultural production with much ease and better efficiency. Agricultural mechanization plays an important role in increasing cropping intensity, precise sowing, and various crop input (seeds, chemicals, fertilizers, irrigation, water, etc.) utilization within a given time, to reduce the arduous labour of humans and animals along with permanent climate problems. Some suitable agricultural tools and techniques have been developed for the crops of this region to reduce the losses in crop production system which is very important to increase the overall productivity and production. This chapter focusses on the mechanized practices used in various farming activities from tillage to threshing and processing through efficient use of input resources for the arid region of Rajasthan. In today's era, robotics in agricultural work, Internet of Things in agricultural equipment, precision farming machinery, conservation techniques, renewable energy use in farm machines, and custom hiring centre should be given attention, so that the increase in demand for food can be met in the future and farmers can get more profit in crop production even in dry areas.

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**Keywords**

Agricultural mechanization · Productivity · Precision farming · Custom hiring centre · Conservation techniques

## 34.1 Introduction

### 34.1.1 An Overview of Agricultural Mechanization

Agriculture mechanization refers to the use of different power sources and improved farm tools, implements, and equipment to reduce labour; increase cropping intensity, yield, productivity, precision metering, and placement of inputs; and reduce crop losses at various stages of crop production. Mechanization requires a lot of capital investment. Investing in mechanization may not deliver the desired outcomes without proper planning and guidance. India's selective mechanization strategy makes agricultural mechanization difficult. This selective mechanization maximizes the use of agricultural resources. Rural landholdings benefit from better human and animal-drawn equipment. Large farms are being mechanized by tractor-drawn and self-propelled agricultural machines. It is necessary to implement a mechanized technique that achieves the demands of farmers.

Landholdings in different parts of the nation must be consolidated (virtual or actual) for their owners to profit from agricultural mechanization. So, timely operations and improvements in equipment and processes should increase quality and quantity in agriculture production. A lack of modern equipment and technology constraints Indian farmers. As a consequence, manufacturing costs are high, and export markets for surplus produce are limited. There are large technological disparities across cropping systems and regions. Using precise and efficient equipment will enhance the quality of processes including seedbed preparation, sowing, fertilization, chemical and irrigation water application, weeding, harvesting, and threshing. Mechanization has so far benefited wheat-based farming systems in India. These advantages must be extended to other agricultural systems, including rice and horticulture.

The availability and efficient use of agricultural electricity by farmers influence agricultural output. Agricultural machinery boosts land and labour productivity by speeding up agricultural activities and increasing output per unit time. The total farm power availability in the country was 2.24 kW/ha in 2016–2017 with a share of 1.324, 0.018, 0.021, 0.460, 0.193, 0.091, and 0.130 kW/ha from tractors, power tillers, combines harvesters, diesel engines, electric motors, humans, and draught animals, respectively (Mehta et al. 2019). In general, they reported mechanization levels of 46% for rice and 24% for sugarcane, wheat, and sorghum, respectively (Fig. 34.1). Small and marginal farmers who cannot afford to buy different agricultural equipment for various field operations now have choices due to the rising trend of establishing custom hiring and hi-tech centres in localities. Tiwari et al. (2019) estimated 3.74 kW/ha agricultural power availability in 2032–2034. They also

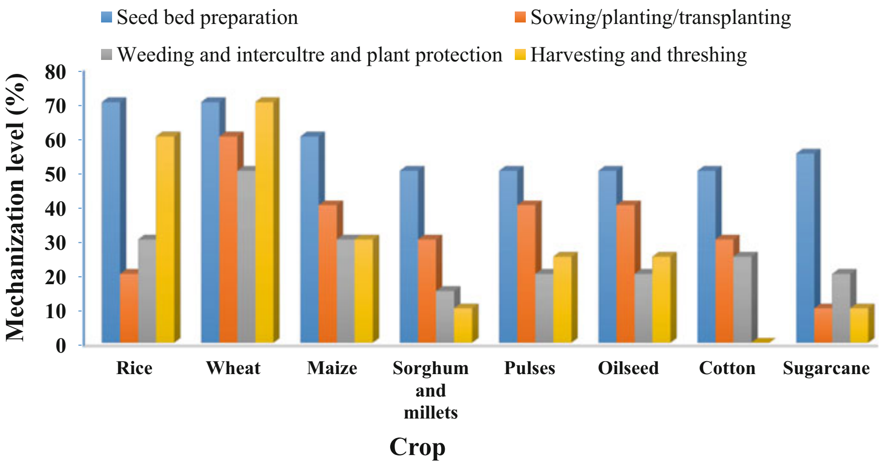

**Fig. 34.1** Agricultural mechanization level for main crops in India. Reprint with permission taken from Modi et al. (2020)

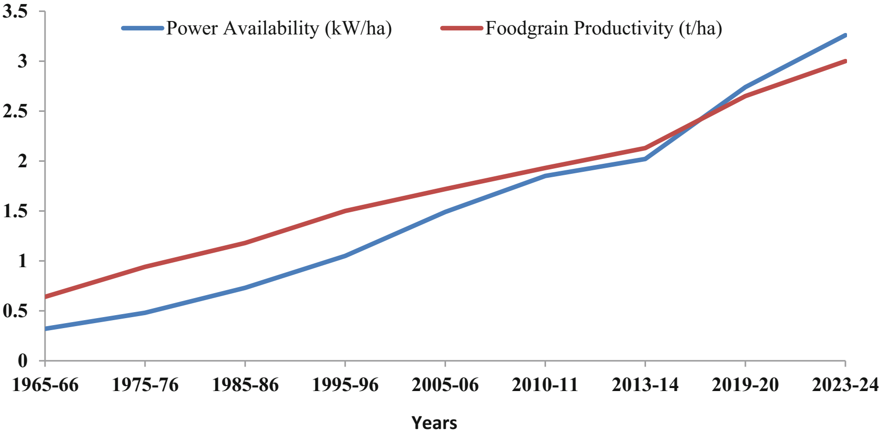

**Fig. 34.2** Relation between power availability and food grain productivity during different periods. Data taken from source: DAC, GOI

estimated a decline in agricultural labourers from 54.6% to 49.9% in 2021 and 25.7% in 2050. The correlation between power and grain production is proportional (Fig. 34.2). Food grain productivity in the country increased continuously from 0.32 kW/ha in 1965–1966 to 2.74 kW/ha in 2019–2020.

Limited natural resources affect agricultural production systems. Inadequate management of these resources and their quality is also influenced by climate variability. Agriculture must be changed to promote sustainability and resistance to the consequences of climate change without compromising food security for all. These issues are interrelated and anticipated to be solved concurrently by smart agriculture. Agricultural mechanization would assist create a climate-resilient agricultural system and enhance earnings via increased agricultural production. Agricultural techniques are required in every region of the world. Arid land is land that is too dry for conventional rainfed agriculture. Millions of people live in such areas, and if present trends continue, millions more will shortly. These people need to eat; thus they should grow their food. However, the strategies are so diverse that only a huge volume could cover them all. Traditional practices may be tough to improve, yet sometimes even basic and economical advances may be revolutionary. This chapter suggests that one must begin to improve local agriculture in arid zones by learning what is already there and future mechanization techniques. Then both techniques and plants that may be useful in specific situations are suggested.

### 34.1.2 Status and Scope of Agricultural Mechanization in the Arid Region

Agricultural mechanization is critical for increasing input efficiency while also increasing output and productivity. Agricultural mechanization methods have been shown in several studies to enhance crop yield and productivity by 10–15%, as well as cropping intensity by 5–20%. It will also save up to 15–20% on seeds, fertilizer, and pesticides, as well as 20–30% on time and labour. In terms of the worldwide situation, Western Europe, the United States, Brazil, Russia, and China have achieved mechanization levels of 95, 95, 75, 80, and 59.5%, respectively (Grant Thornton 2017). On the other hand, India has only attained a mechanization level of 40% (Mehta et al. 2019). Haryana, Punjab, and Uttar Pradesh are the top states in India, while other states lag behind. The availability of agricultural electricity in Rajasthan grew from 1.14 kW/ha in 2014 to 1.37 kW/ha in 2017; however, it is still quite low when compared to the top states (Ministry of Agriculture and Farmers Welfare, Mechanization and Technology Division, GOI). Tractor adoption is on the increase, while other agricultural implements are still in the minority. Farm mechanization is constrained by the dispersion of farm sizes. Rajasthan state has a notably distinct pattern when compared to India's average farm size. On average, the size of a farm in this state is bigger than in the rest of India. Farmers who operate a field of up to 2 hectares account for 58% of all holdings, whereas on average, they account for 85% of total holdings. When compared to the national average, small, semi-medium, medium, and large landholdings account for a larger share (Table 34.1).

**Table 34.1** Average farm size in Rajasthan versus India

| Type of holding | India (%) | Rajasthan (%) |
|---|---|---|
| Marginal (< 1 ha) | 67.1 | 36.5 |
| Small (1–2 ha) | 17.9 | 21.9 |
| Semi-medium (2–4 ha) | 10.0 | 19.4 |
| Medium (4–10 ha) | 4.2 | 16.4 |
| Large (> 10 ha) | 0.7 | 5.9 |

Source: Department of Agriculture Rajasthan (2011)

Reduced supply of agricultural labourers is predicted to drop by about 26% by 2050. Cooperative organizations, custom hiring centres, and farmer groups are all possibilities in today's Indian agriculture. Financial assistance to local manufacturers via the Make-in-India programme to build agricultural machinery or equipment that meets local needs rather than depending on imports from industrialized nations. Small-scale mechanization and custom-hiring centres are quickly becoming viable options for small-scale farmers.

The Indian arid zone covers 31.7 mha, with the majority of it in north-western India (28.57 mha) and some in southern India (3.13 mha). The Great Indian Desert, often known as Thar, included major portion of the arid regions of Rajasthan and minor portion of Gujarat, Punjab, and Haryana. The western Rajasthan encompasses around 61% of the country's total hot arid areas, making it the country's primary hot arid region (Tewari et al. 2014). Arid soil covers around 12% of India's geographic area. Rajasthan, Punjab, Gujarat, Haryana, Karnataka, Maharashtra, and Andhra Pradesh are all part of it. Overexploited vulnerable natural resources in India's arid areas are mostly under mixed farming, which is virtually exclusively rainfed with poor and unreliable yields. Crop yields in this zone are heavily influenced by the weather. The weather observed as irregular rainfall (100–450 mm) and extreme temperatures (usually>45 °C in peak summer and sub-zero in winter) and high summer winds of more than 30 $\mathrm{kmh}^{-1}$ during summer. These are the ever-present climate issues, particularly for agriculture. Cropping in the Indian arid areas has always been seen as subsistence rather than a commercial operation due to socio-economic conditions. Most farmers in subsistent farming resort to producing certain rainfed crops on farm solely to meet their household requirements and rotate a specific crop mix over 3–4 years. That results in multitude of cropping systems which are constantly changing in location and time, making it impossible to accurately evaluate the distribution of various cropping systems across a larger area using the conventional method.

The opportunity for growth in Rajasthan would be severely limited unless agricultural production risks are minimized. Soil moisture management is the single most significant aspect in lowering the risk. With the region's limited surface and groundwater resources, further extension of conventional irrigation with poor water yield will be impossible. Prerequisites for the growth of the region's agriculture include soil moisture conservation, precise irrigation to achieve the maximum potential water productivity, and utilization of the limited water supply for the high-value crops. In rainfed regions, coarse cereal crop production will continue to dominate due to its capacity to survive in drought and low water requirement. It is necessary to incorporate equipment and technology for the planting, harvesting, and threshing of coarse grains such as pearl millet. It is necessary to plant seeds deep in the soil to take advantage of the depleting soil moisture. Farmers in the region should have access to sufficient power and matching equipment for timely land preparation and precision planting of various coarse cereals and other rainfed crops of arid region. Also, to make the efficient utilization of soil moisture available for crop establishment stage before the soil top layer dries out. To maintain agricultural production in arid areas, suitable mechanization methods matched to the requirements of farmers must be adopted.

### 34.1.3 Rajasthan Government's Initiatives for Farm Mechanization

The last two decades between 2000 and 2010 was a period with a major boom in agricultural machinery manufacturing for mechanization. In these decades, John Deere, Mahindra & Mahindra (M & M), New Holland, and Tractors and Farm Equipment Limited (TAFE) built their manufacturing units in India, and the Indian manufacturers started operations overseas in rural areas of our country as well as our state. In addition, according to Singh (2015), the implementation of the new scheme of our country Mahatma Gandhi National Rural Employment Guarantee Service has had a tremendous socio-economic impact on agricultural labour and improvement in their social status. This situation has offered a considerable boost to mechanization.

Rajasthan Agriculture is witnessing a significant movement from manual to mechanical power; the shift is mainly because of unavailability and the high cost of labour at farms. Further, the mechanical power directly influences the quality of farm operations which in turn increases the crop productivity, timeliness of agricultural operations, and reduction in drudgery. In November 2016, the Government of Rajasthan (GOR) signed an agreement with EM3, TAFE, and Mahindra & Mahindra to set up, launch, operationalize, supervise, and certify Custom Hiring Centres (CHCs) across Rajasthan. In this context, EM3 is responsible for establishing more than two hundred centres according to mass to provide mechanization services to one lakh farmers in 28 districts of the state. EM3 works with different business models in the states where it operates. In the case of Rajasthan, the start-up has decided to work with a franchise model to procure the equipment required to fill the existing machinery and technology gaps in the state. In addition, Tractors and Farm Equipment Limited (TAFE) has set up JFarm Rajasthan, an advanced agricultural research centre in Bhawani Mandi, Jhalawar District, in November 2016, which will facilitate the farmers of Rajasthan to hire tractors and modern farming machinery. TAFE has entered into an agreement with the government to set up CHCs in six identified zones (Bharatpur, Jodhpur, Jaipur, Jalore, Kota, and Sikar) across the state (TAFE 2017). TAFE's agreement with the Government of Rajasthan focusses on two initiatives – Custom Hiring Centre and JFarm. Rajasthan Center of Excellence with an estimated total cost over five years. Through agreements worth Rs 970 crores with the Rajasthan government in the agriculture sector of Rajasthan, JFarm Services expects to partner with 900 farmer entrepreneurs, create 4000 jobs, and touch the lives of 500,000 farmers.

The implementation of the Sub-mission on Agricultural Mechanization (SMAM) program by the Ministry of Agriculture is therefore a step towards ensuring last-mile reach of agricultural mechanization to small and marginalized farmers (Government of India 2018a, 2018b). Apart from SMAM, the government also promotes agricultural mechanization programs through other missions/schemes like Mission for Integrated Development of Horticulture (MIDH), Rashtriya Krishi Vikas Yojana

(RKVY), and Oilseeds and Oil Palm (NMOOP) (Government of India, National Mission) (Government of India 2016–2017). However, CHCs for farm implements were set up in 100 NICRA villages which could successfully empower the farmers to overcome the labour shortage and improve the efficiency of agricultural operations. A committee of farmers nominated by the Gram Sabha manages CHCs. Rates for hiring machines/tools are set by the Village Climate Risk Management Committee (VCRMC). The committee also utilizes the proceeds from the hiring charges for the repair and maintenance of the equipment, and the rest goes to the revolving fund. 27 different types of agricultural machinery are stocked in 100 CHCs. The most popular are rotavator, zero till drill, drum cider, multi-crop planter, power weeder, and chaff cutter. Each centre was set up at a capital cost of Rs. 6.25 lakhs funded by the NICRA project. As a result of government initiatives and equal participation of the private sector, agricultural mechanization has been steadily increasing in recent years, which can be seen in the increase in production, sales, and export of tractors from the country. CHCs and innovations in the agricultural machinery sector, therefore, have the potential to drive the next phase of agricultural development in India. Thus, there is a need for a congenital policy framework to encourage setting up of community health centres as the preferred business model in the country so as to efficiently bridge the gap between need and availability. Increasing awareness and knowledge of farmers through various stakeholders in the agricultural supply chain and involving farmers' investments in implementing future plans and policies can lead to better value creation.

## 34.2 Farm Mechanization in the Arid Region

Farm mechanization includes machinery involved in farm operations, viz. tillage, sowing, transplanting, fertilization, weeding, irrigation, protection, harvesting, threshing, waste management, and transportation. Some of the machinery, tools, or implements have been recommended for arid regions as presented in Table 34.2. These agricultural implements may be utilized in arid region for efficient utilization of input resources for crop production and productivity.

### 34.2.1 Tillage

Tillage is one of the operations for manipulating the soil mechanically. It's required for weed control and to bring out the optimum tilth and physical environment of soil for crop establishment and proper germination. In this context, soil tilth is meant for the physical condition of the soil describing its cone index, bulk density, roughness, porosity, and structure related to nutrient, water, air, and heat transport. Tillage is highly mechanized (exceeding 50%) for major crops of India (Mehta et al. 2019). It is usually categorized as primary and secondary and depends largely upon the rainfall and soil type. Some of the methods have been described hereunder.

**Table 34.2** Details of agricultural machinery, implements/tools of the arid region

| Operation | Agricultural implements and machineries |
|---|---|
| Tillage | |
| Tractor | Mould board plough, disc plough, tyne type cultivator, disc harrow, rotavator, pulverizing roller, cultipacker, cage wheel |
| Power tiller | Rotavator, mould board plough, cage wheel |
| Animal | Mould board plough, camel-drawn 2 and 3 tyne plough, ridger, camel-drawn harrow, blade harrow, disc harrow 6 disc, harrow patela |
| Manual | Pick-axe, spade, trenching hoe, garden rake |
| Land levelling | |
| Tractor | Tractor-drawn leveller, laser-guided land leveller, scraper, planker (Pata), variable width raised bed former |
| Animal | Camel-drawn bund former, buck scraper, clod crusher |
| Manual | Spade, scraper |
| Sowing and fertilizer | |
| Tractor | Seed drill, seed cum fertilizer drill, maize planter, groundnut planter, cotton planter, fertilizer broadcaster, zero till drill, strip-till drill, rapeseed-mustard seed drill, ridge planter for maize, ridger seeder, multi-crop planter, pneumatic precision planter, mulcher-cum-bed planter, vegetable transplanters, small seed planter, broad bed and furrow (BBF) planter, furrow irrigated raised bed (FIRB) planter, turbo happy seeder, garlic planter, turmeric rhizome planter, BT cotton planter, ridge fertilizer drill cum seed planter, semiautomatic vegetable transplanter |
| Power tiller | Lightweight multi-crop planter, site-specific fertilizer applicator |
| Animal | Camel-drawn seed cum fertilizer drill 2–3 rows, seeding attachment over deshi plough, maize planter, groundnut planter, cotton planter, indigenous seed drill, CRIDA drill plough, Jyoti multi-crop planter |
| Manual | Dibbler, push-type seed cum fertilizer drill, seed drill |
| Weeding and intercultural | |
| Tractor | Cultivator, cultivator with duck foot shovel, high clearance weeder, garlic weeder, rotary weeder, mechanical intra- and interrow weeder |
| Power tiller | 5–7 tined cultivator, self-propelled power weeder, sweep tyne cultivator |
| Animal | 3–5 tined cultivator, ridger, improved bakhar |
| Manual | Wheel hoe, V-blade 3 tined hoe, kudali, power weeder, dryland peg weeder |
| Irrigation | |
| Tractor | Irrigation channel former, subsurface drip laying machine, drip lateral-cum-plastic mulch laying machine |
| Power tiller | Irrigation pump attachment |
| Animal | Plastic mulch laying machine, Persian wheel, duplex pump |
| Manual | Diaphragm type low lift pump |
| Plant protection | |
| Tractor | Real-time uniform sprayer, mini tractor-operated field sprayer, centrifugal prayer, aero-blast sprayer, boom sprayer, motorized knapsack power sprayer cum duster, ultrasonic sensor-based pomegranate spraying system |
| Power tiller | Sprayer attachment |

(continued)

**Table 34.2** (continued)

| Operation | Agricultural implements and machineries |
|---|---|
| Animal | Solar-powered sprayer, sprayer attachment |
| Manual | Knapsack sprayer, hand compression sprayer, backpack sprayer, foot sprayer, duster, wide-swath spray boom for tall crops, solar-powered bird scarcer |
| Harvesting | |
| Tractor | Vertical conveyor reaper, cotton picker, reaper binder, tractor-drawn combine, groundnut digger, millet harvester, cotton stalk puller, hydraulic-operated pigeon pea harvester, cassava harvester, straw reaper, straw baler |
| | Self-propelled reaper binder, combine harvester, straw combine, scythe |
| Power tiller | Carrot harvester cum detopper |
| Animal | Groundnut digger |
| Manual | Improved sickle, sugarcane stripper |
| Threshing | |
| Tractor | Multi-crop thresher, maize dehusker cum sheller, single row corn cob picker |
| Power tiller | Multi-crop thresher |
| Manual | Pedal-type paddy thresher, groundnut stripper, tubular maize sheller, burr-type maize sheller, pedal-operated maize dehusker sheller, winnowing fan |
| Straw management | |
| Tractor | Wheat straw collector, cotton stalk shredder-mixer, paddy straw bale shredder-cum-mulcher, baler |
| Animal | Bullock drawn chaff cutter, camel-drawn chaff cutter |
| Manual | Hand chaff cutter |
| Transport | |
| Tractor | Trolley, trailer |
| Power tiller | Trailer |
| Animal | Camel cart, bullock cart, 4-wheel camel cart, 2-wheel camel cart with jeep tyres |
| Manual | Hand cart with solid rubber wheel |

Sources: Ministry of Agriculture and Farmers Welfare, Mechanization and Technology Division, GOI; ICAR-CIAE annual reports (2014–2019); Singh et al. 1998; Jangid et al. 2010; NRC on camel report (2003).

In western parts of Rajasthan, the harrow is commonly used with patela for tillage operations. Conservation tillage is another method for conserving water, soil, and energy by reducing the tillage intensity and mulching of crop residues. It has different types, viz. zero till, mulch till, strip-till, and ridge till. It is associated with the minimum disturbance in soil in seeding, growing, planting, and harvesting of the crops. Zero tillage/no-tillage is one of the alternatives to conventional methods for seed bed preparation. It increases the carbon content at top soil (Lenka and Lenka 2014). Rotary tiller helps in mixing fertilizer or manure while mixing weeds with the soil. Rotavator has reduced the operation time and cost by 30–35% and 20–25%, respectively (ICAR 2007). The simultaneous operation of two or more tillage implements is referred to as the combined tillage. Combination tillage reduces soil compaction, the time required for field operation, labour cost, and fuel cost. The time and cost reduction have been estimated as 50–55% and 44–55%, respectively, during seed bed preparation (Prem et al. 2016). It has a performance index higher than the same for conventional tillage. Laser levelling is used for very fine levelling of the agricultural field with the application of laser, which helps enhance the crop yield. Cook and Peikert (1960) reported it is helpful in reducing the irrigation water requirement by 20–25%. A controlled wheeling system becomes advantageous in terms of extra output with a reduction in variable cost. McCrum et al. (2009) reported it is useful in reducing the power requirement by 30% as a result of improvement in soil structure. So, these are some mechanized tillage and land levelling operations that can be used in arid regions for efficient utilization of natural and input resources for crop production.

### 34.2.2 Sowing/Transplanting

Sowing or transplanting is one of the operations intended to have desired crop yield. It becomes difficult to operate manually due to labour shortage in the specific period of the operation. The crops may get affected if sowing or transplanting is delayed. Thus, mechanization plays role in precision, timeliness of operation, cost-effectiveness, and input efficiency with resource conservation. The technologies commonly used in the arid region have been enlisted here in Table 34.2.

However, tractor-drawn three-furrow (six-row), multi-crop seed cum fertilizer drill has been developed for sowing the crops on slant surfaces especially with a created furrow with seed-pressing device (Fig. 34.3). The furrows are meant for

**Fig. 34.3** Tractor-drawn seed cum fertilizer drill for sowing the crops on slant surfaces

collecting the runoff water for maintaining high moisture concentration in the plant root zone. It resulted in an increase in plant height and grain yield by 26% and 30–70%, respectively, as compared to the same for the conventional method. The grain yield could be increased by 30–40% as compared to the same with the conventional method for green gram, moth bean, pearl millet, and cluster bean crops with normal rainfall of 389.3 mm/year. However, the increases in grain yield have been recorded up to 60–70% with severe moisture stress during kharif (Singh et al. 2007). This technology has great potential of getting popularized for improvement in crop production of the arid region.

### 34.2.3 Weeding and Intercultural Operations

Weed control is targeted to reduce the competition of crops for nutrients, water, and sunlight. Some of the improved weeding tools are peg tooth weeder, slotted hand hoes, and two/three tyne animal-drawn shovel. Mechanical weeding is recommended before applying the chemical method to eradicate the weeds and make water availability to the crops. The yield loss is associated directly to weed competitiveness. Rao and Chauhan (2015) estimated yield losses in India as 10–100% (Fig. 34.4).

As the arid region is having light-textured soil, a pull-type weeder is conveniently used manually. Traditional Kassi is usually used in the region. It has problems of high pull requirement (8.5 $kg_f$) and removal of worked soil from the blind face of Kassi. The field capacity was found maximum with double slot weeder as 193.4 $m^2$ $ha^{-1}$ with 94.5% as the weeding index. Their respective values were 165.3 $m^2$ $ha^{-1}$ and 98.5% for single slot weeder whereas 160.5 $m^2$ $h^{-1}$and 91.8%

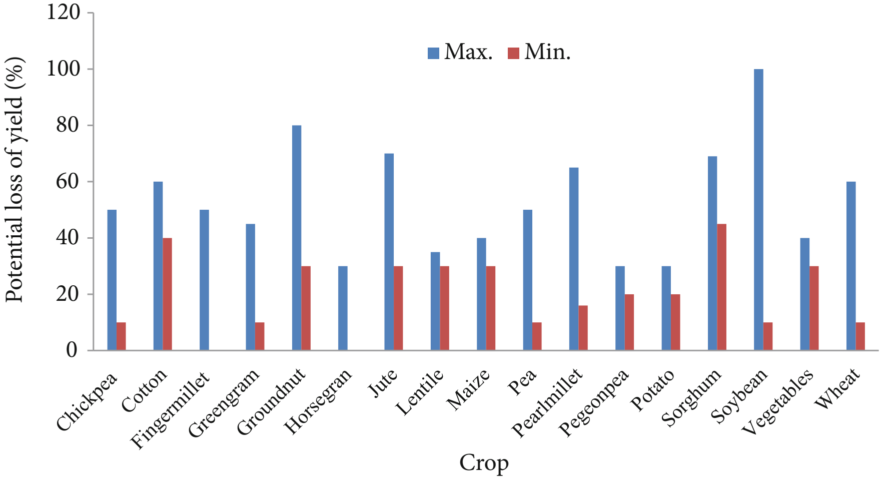

**Fig. 34.4** Maximum and minimum potential yield loss due to weeds in major crops of India. Data obtained from Rao and Chauhan (2015)

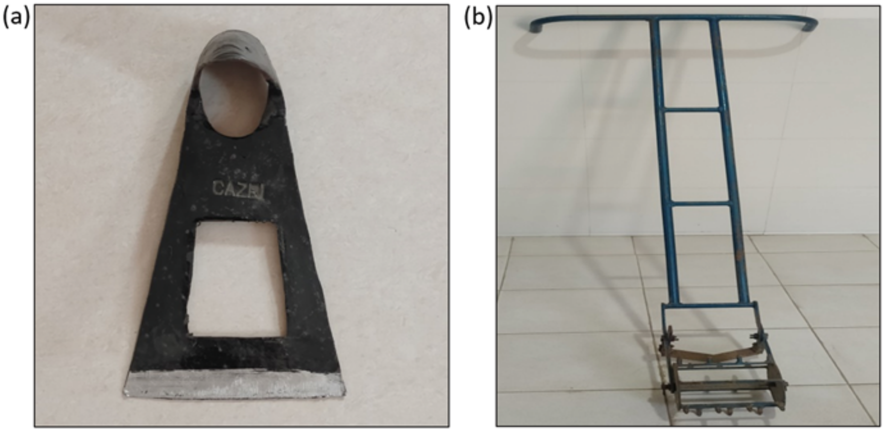

**Fig. 34.5** (**a**) Improved Kassi; (**b**) crust breaker

for traditional Kassi. The problem of soil accumulation was resolved through an appropriate slot made in the blind face of Kassi. It could reduce the pull requirement by 40% and thus suited to women and younger farmers. Weeder was found best suited to men with 130 mm width, which requires 65% power with 20% greater field capacity as compared to the traditional Kassi (Fig. 34.5a). Single slot Kassi has preferably been used due to its convenience in operation.

The germination is affected due to crust formation in the soil as a result of sand deposition at the upper surface of the field. This problem could be resolved using a manually operated crust breaker. It consists of a peg type wheel followed by a blade for uprooting the shallow weeds with a long handle (Fig. 34.5b). It is operated manually between two rows of crops in a standing position through push and pull action. It cuts weed while creating soil mulch by breaking the soil crust. The sharp pegs penetrate the upper layer of soil and resulted in a break in the hard crust. Thus, the rear blade helps uproot the weeds. It requires 90 man-hours for crust break operation of a one-hectare area with 78.9% of the weeding index and 3.8% of minimum plant damage.

The mechanical weeding tools, viz. hand hoes, animal drawn weeders, power weeders, manual operated push-pull-type weeders, and tractor-operated row crop cultivators, are used in crop rows for weeding the plants. The conventional weeding methods are time-consuming, laborious, and costly, and thereby various researchers have aimed to mechanize the operation. The intercultural operation in the horticultural crops seems difficult due to its crop canopy and reach of the regular implements. A tractor-mounted offset rotary tiller or rotavator is an implement which can be used for the pulverization of soil as a secondary tillage operation as well as weeding purposes in fruit tree orchards and agroforestry fields. Using an offset rotavator makes it easier to remove weeds under and around a plant canopy. This allows us to do inter-cultivation operations in an efficient way which leads to saving time as well as drudgery. The era of intelligent weeders has come with sophisticated ways for controlling the weeds and leaving crop plants undamaged. This includes innovative technologies, viz. machine vision, robotic weed control systems, and RTK GPS guidance systems intended for a significant reduction in weeding time and drudgery.

### 34.2.4 Irrigation

Water is an important resource for plant breeding and living in arid regions. It leads to the adaptation of very few species with increased aridity and reduced biomass. Plants are thus recommended to be grown in an arid region with the help of some of the mechanisms. Due to scarcity of water, it is difficult for plants to compete with weeds. Water quality is another problem of the arid region resulting in soil salinity and thereby limiting crop production. Thus, water management of the region encompasses water collection, conservation, and efficient utilization while avoiding its losses through infiltration or runoff.

India is a vast country with wide variations in rainfall patterns with the occurrence of drought in some parts of the country. A large portion (65%) of the country is practicing rainfed agriculture (Singh et al. 2013). Thus, water use efficiency is always of prime concern for researchers of different disciplines. In the event of inadequate rainfall, water is poured into the soil through artificial application for crop cultivation, habitat preservation, and improving the degraded soil in the arid region. It encourages adapting the irrigation system for crop plants with reduced cost and wastage of water. Mechanization of irrigation system is thus required to take care of the wastage through evaporation, seepage, and deep percolation. It leads to micro-irrigation systems as modern methods of irrigation. A micro-irrigation system is in demand due to its association with a significant reduction in water wastage. Government schemes are also encouraging it to adapt through subsidy. It is usually categorized as sprinkler system, surface system, and drip system. The sprinkler system is operated in the form of spraying water using the overhead sprinklers, whereas the drip irrigation system is the water application in the plant root zone.

Dryland farming is an important component of the growth of Indian agriculture. Phule check basin has been found to contribute tremendously to the dryland farming of Maharashtra through rainwater harvesting. The check basin of 6 m × 2 m size assists for 30–40% timeliness with 50–60% saving and increased production in the rabi season (Turbatmath and Deshmukh 2016). As groundnut yield is declined by 10–15% in the rainfed condition due to delay in sowing by 1 week, the aqua planter has been designed and developed to resolve the issue (Laxman et al. 2018). It ensures seed sowing with simultaneous application of required water for germinating the seeds. Thus, the technology is advantageous for dryland farming. Integration of an aqueous fertilizer tank with the aqua planter can improve germination and crop growth at initial stage rainfed conditions. It is powered by a 45 hp. tractor with a field capacity of 0.25 ha/h. The machine consists of liquid fertilizer tanks (2pcs), a fluted roller seed metering mechanism, and a constant head central tank. Wheat cultivation has been investigated with the increase in germination and yield by 53 and 35%, respectively. Water absorption increased by 350 times using the hydrogel to make water available to the plant roots in the stress condition. The hydrogel applicator can also be attached to the aqua ferti seed drill or seed cum ferti seed drill (ICAR-IARI 2022).

### 34.2.5 Plant Protection Operations

Chemical application is practiced for saving crop plants from insects, weeds, and diseases. It may be in either the form of dust, spray, or mist. The chemical application requires efficient equipment for its judicious use due to health issues and the cost involved. A duster is simple and commonly used for chemical applications and best suited to portable equipment. However, sprayers are more efficient as dust has less retention capacity. It is used for various applications, viz. insecticides, herbicides, micronutrients, and protective fungicides. Sprayers are meant for splitting liquid into droplets and distributing the same uniformly over the space or surface to be protected. It is useful in regulating the operation to avoid excessive application of chemicals. Sprayers of different types have been designed and developed for the specific crop and field. Some of them are foot sprayers, knapsack sprayers, hand compression sprayers, twin knapsack sprayers, motorized knapsack mist blower cum duster, and centrifugal rotary disc-type sprayers. Presently, ultralow volume sprayers are in practice for the application of concentrated pesticides with the help of special nozzles and the development of new formulations. Controlled droplet application atomizer is considered suitable for arid regions due to ease of operation and requiring spray mixture less than 15 L/h.

The chemical applicators may be integrated with solar photovoltaic cells for power requirements. In a study, the sprayer achieved 84 L/h of application rate with 0.21 ha/h capacity, but the same was varying with solar irradiation (ICAR-CAZRI 2016–17). Dusters are also linked to solar power for application in the arid region of Rajasthan. The recent advancement in technological intervention has reached the era of sensor application for identifying and monitoring the infested location, infestation level, and GPS-mounted sprayers. Thus, precise application of pesticides leads to effective control of pests with saving of pesticides as compared to the conventional method of pesticide application (Dworak et al. 2013). Autorotating-type gun sprayer is recommended for efficient and effective spraying at the rate of 375–1000 litres per hectare with 30 min wide swath and 3–4 ha/h capacity for controlling the sucking pests, viz. whitefly in cotton.

It is still difficult to spray the chemicals as one has to walk through the standing crop and thereby high clearance vehicles are used. PAU (Punjab Agricultural University, Ludhiana) has developed a sprayer consisting of autorotating gun with boom and drop up type of mechanism. It can spray effectively at all stages of crop growth with high clearance. A tractor is also developed with high clearance and narrow rear tyres for mounting the spraying systems. The high clearance sprayer has field capacity and breakeven point of 1.78 ha/h and 300 ha/year with labour, time, and cost savings up to 95, 95, and 66%, respectively, as compared to the knapsack sprayer (Singh et al. 2018). Electrostatic spraying has subsequently improved the efficacy and spatial distribution of droplets throughout the plant canopy. The air-assisted electrostatic sprayer has been developed as a mobile backpack (MBP) type with 5 hp. engine and a non-board compressor. A spray gun is also developed with 9.0 V rechargeable batteries (2 Nos.) to charge the spray particles. It can increase the spray deposition on the upper side and underside by 80 and 85%, respectively, as compared to the knapsack sprayer. Electrostatic sprayer drift loss is 50% lesser than the same for knapsack sprayer. Bio-efficacy, the percentage of insects killed, has been estimated 68% higher than the manual operated knapsack sprayer (Singh et al. 2018). However, recent advancements comprised drone application and spraying attachment (Kumar et al. 2018). These technologies are recommended for the efficient application of pesticides in the arid region.

### 34.2.6 Harvesting and Threshing

Mechanization index in harvesting and threshing operations increases up to 60–70% for rice and wheat, but for other crops, it is less than 30% (Mehta et al. 2019). Around 5000 combine harvesters are sold annually in India. Indigenous models are of Standard, Kartar, Dashmesh, and Preet companies, while foreign manufacturers like Kubota, CLAAS, and John Deere are also exporting their developed combine harvesters in different regions of India. Combines may be tractor drawn or self-propelled type. Track- and wheel-type self-propelled combines are commonly used. Track-type combines have good traction to work in sticky and wet-type soil for harvesting in the south.

About 90,000–1, 00,000 threshers are sold annually in different parts of India. Manufacturing of threshers is done by huge amount of small- and medium-scale enterprises (SMEs) situated in the state of Punjab, Haryana, Gujarat, Uttar Pradesh, Madhya Pradesh, Maharashtra, Bihar, Andhra Pradesh, and Tamil Nadu. The thresher market is likely to develop at a compound annual growth rate (CAGR) of 10 per cent. Threshers are applicable in hilly terrain or other difficult areas or marginal farmers that are unable to recompense the cost of operation by the combine. There are different types of threshers available in the Indian market like wheat thresher, basmati thresher, paddy thresher, and multi-crop thresher for efficient threshing of crops with the minimum grain damage. Multi-crop threshers are used for the threshing of soybean, millets, oats, wheat, barley, sorghum, chickpea, and pulses. Threshers are operated with a 35–70 hp. tractor or electric motor of 7.5 hp. or a diesel engine of 10 hp. and give grain output capacity of about 1200–2500 kg/h. Ergonomics is applied to some design modifications in harvesting and threshing machinery to make them ergonomic for human use and adoption as per region-specific requirements.

## 34.3 Socio-Economic Aspect of Farm Mechanization

### 34.3.1 Drudgery Involved in the Farm Operation

Agricultural activities are performed in an unfavourable ergonomic posture, including repetitive body movements, long periods of operation, machine noise and vibration, etc. that may cause musculoskeletal diseases, awkward posture, and discomfort. Agricultural machinery should be designed and manufactured to be safe when used properly. The machine should be operated and maintained following the manufacturer's instructions. Machines should be equipped with safeguards or secure storage for potentially hazardous parts. In addition to the amount of physical and mental workload, stress and exhaustion are also associated with variables such as posture, environmental parameters, and certain psychological factors. Inadvertent disregard of ergonomics in the design, development and various instruments operation, and machines has resulted in many injuries and fatalities in various agricultural operations. Particularly in conventional agriculture, there are concerns about difficulties, drudgery operations, slow work processes, and other work organization challenges (such as basic tools and procedures) where ergonomics can help by contributing to aspects of work efficiency and product justification. Because technologies apply high physical stress, they should not be applied. However, there are occasions where ergo-design benefits health and comfort.

Various agricultural research institutions/industries have designed, developed, and promoted several improved implements to reduce the drudgery of various agricultural activities performed by human labour. However, only a few respondents in the research area owned them. The knapsack hand sprayer took first place among the improved manual operated equipment owned by respondents, with 12.24%, followed by foot sprayer (1.69%), groundnut decorticator (1.27%), and duster (0.42%). Even though maize is the most significant kharif crop in the area, none of the respondents had improved sickles or maize cob shellers (Jangid et al. 2010). Having solutions in place that satisfy design and operating requirements is important for machinery and equipment safety. Machine designers/developers and manufacturers are responsible for design requirements. Users are accountable for providing harmless working surroundings for their work and must meet operating standards. Machines and equipment should be developed, manufactured, and operated following machine functioning and intended usage to ensure that equipment and machineries can be serviced and modified safely. Such requirements include ergonomic criteria. They ensure the proper functioning of human users and operators of technical equipment. Design-related requirements are a top priority for safety. While they promote the use of technological equipment, safety ultimately depends on meeting specific operational criteria (Górny 2017). Work requires resources that allow it to be done without undue strain or hindrance. Workplace resources include tools and equipment (Gite et al. 2020). The knowledge of people's psychological and physical abilities is an important necessity for machine and equipment design. These requirements ensure the safety of operation once satisfied. It includes the correct equipment design and development.

Given the fact that operators must operate machines in the field, ergonomics considerations during the application of agricultural equipment are extremely important for them to consider. Because ergonomics contributes to the creation of human comfort, it will help the operator successfully operate the machine while delivering the required level of productivity. To improve operators' performance, the workplace on agricultural machinery needs to be comfortable and safe. During agricultural operation, frequently operated controls should be within the reach of the operator for easy and comfortable operation, a reduction in physical workload, improving the working efficiency, and preventing accidents (Shukla et al. 2021).

### 34.3.2 Cost-Economics of Agricultural Machineries

As presented in different studies, direct relationship between farm mechanization and crop yield. Farm mechanization helps in many input savings and increased cropping intensity. An arid and semiarid region of Rajasthan state, rainfall pattern varies abruptly, so timely sowing is most important to increase crop production efficiency. The cost of deploying labour for agriculture operation is increasing substantially. Farm mechanization is the only alternative to dealing with the increasing cost of labour and timeliness of field operations. Survey work among farmers has revealed that nowadays majority of farmers are using tractors for agricultural operations on their land. Even then, they have to use camels for ploughing some of the portions of their land which cannot be covered by a tractor, viz. sand dune portion. Apart from that, if the sand storm comes and one needs to plough, the camels are used for that purpose. Some of the farmers exclusively use camels for agricultural operations. Single and double plough shares are used in large amounts. Sowing of groundnut requires both tractors and camel. Initially, the tractor is used for pulverizing the soil, which is then sown with a camel. A camel can plough 0.76–1 hectares land in a day. Putting more labour, it can be possible to cover even 1.52 hectares of land. In groundnut sowing on land previously pulverized with a tractor, a camel can cover only 0.25–0.38 hectares in a day. Camel has been an extremely useful animal of the desert, which can be used in multifarious modes of functions such as pack animal, to pull cart, to pull agricultural implements, and for riding purposes. As a pack animal, it can bear a load equal to 225–295 kg and travel 32 km in a day at a speed of 3–4.5 $\text{kmh}^{-1}$. It can pull a camel cart with loads of 18–20 quintals for 20–30 km in a day. Riding for a distance of 30–40 km can be accomplished per day (ICAR-NRC on camel 2003).

An analysis has been done on cost-economics of the tractors and animal use power for agriculture in the arid region. It was shown that nearly 50% of the area is sown by tractors, 26.36% by camels, and 18.5% by bullocks. Coverage varies with the number of days of use of animals and tractors. The benefit-cost ratio for a tractor, a camel, a single bullock, and a pair of bullocks has been estimated at 1.39, 1.06, 0.85, and 0.86, respectively, for maximum utility by considering agricultural and transportation operations. Similarly, the benefit-cost ratio for a tractor, a camel, a bullock, and a pair of bullocks were found at 1.52, 1.43, 1.3, and 1.07, respectively, considering the owner himself is the operator (Singh et al. 1995). The results are indicative of the significance of tractor and animal power in arid regions. The main factors affecting tractorization in the region were irrigated areas and draught power. Tractorization of agriculture can get a fill in the region with irrigation and significant reductions in draught power as well as profitability for crop production.

## 34.4 Future Mechanization Pathway through IoT-Based Technologies

Currently, agricultural technology serves as a feeder for consumers. A paradigm shift in agriculture requires innovative approaches to agricultural mechanization to maximize productivity. One approach is to use accessible IT in the context of smart devices, increasing and achieving energy output more efficiently than ever before. On the other hand, precision farming has proved to be effective; now is the time to move towards a new generation of equipment/mechanization. Although existing human operations are effective in large areas, there is potential for increasing the size of autonomous system services that can contribute to improved efficiency. Therefore, adherence to realistic precision approaches in agricultural machinery along with other measures to improve agricultural productivity from 140 mha of restricted cultivable land under the scarcity of natural resources and climate change problem to feed growing population (NAAS 2016). This will enable immediate measures to encourage agri-service providers to avail the benefits of agricultural mechanization from small and marginal farmers through farmers' cooperatives/custom hiring centres/machinery banks. The introduction of autonomous AI architecture enhances the potential to build a whole new range of agricultural machinery based on smart machines that can function properly. The adaptation of these technologies should be commensurate with the complexity of the actual situation and the environmental conditions/climate-smart in the agricultural production scenario. Some of such technologies are described below for agricultural sustainability in arid regions.

### 34.4.1 Mechatronics

Mechatronics systems are used in various application fields, like agriculture, automobile, safety, lifestyle, consumer goods, etc. Mechatronics is a collaborative combination of mechanics, electrical, electronics, computers, and control systems. Mechatronics has many useful uses in farming systems. Mechatronics components, such as actuators and sensors, play an important role in vegetation monitoring as well as in sowing, harvesting, and fertilizer application. The use of IoT in agriculture is pushing the boundaries of the mechatronics engineering stream beyond traditional methods. Some mechatronics applications can be used in automatic sowing methods, application of pesticides, and weeding applications. Mechatronics-assisted metering system in seed drills/planters can eliminate many of the inefficiencies experienced in a mechanically operated seed measuring device and have the potential to increase crop yield and productivity dramatically on tillage and no-tillage lands. The mechatronics-based system observed good seeding uniformity among all seeding technologies with quality of feed index, missing index, multiple index, and precision index in the range of 90–98, 0–11, 0–7, and 1–22%, respectively, under the speed of 1 to 16 km/h (Gautam et al. 2019). In this way, current and future mechatronics are being developed on the basis of technological advances required to extend and build human life easier and sustain the world.

### 34.4.2 Precision Agriculture

Precision agriculture has revolutionized the agricultural production sector in recent decades. It is a newer field of agriculture that focusses on optimizing input efficiency while maintaining production and involves vast amounts of data, such as field reference points, control variables, time, state, and meteorological data. These machines demand trained personnel and computer experts for their operation, care, and maintenance. Smart agriculture is the advancement of precision agriculture, in which farm management is remotely controlled by alternative relevant solutions in real time. It mentions the use of new technological innovations in agriculture to improve crop quality and quantity and enables observing variations in climate, soil moisture, and different soil properties. Smart irrigation, fertilization, and spraying improve the quality of produce, fertilizer management, and disease prediction in crops. The smart irrigation system has smart controls, sensors, and mathematical relationships for the measurement of water level, irrigation efficiency, and climate. IoT technology can connect remote sensors like robots, ground sensors, unmanned aerial vehicles (UAVs), and drones, allowing components to be linked together and controlled automatically for real-time harvesting, seedling, weed identification, irrigation, pesticide spraying, livestock applications, etc. (Mohamed et al. 2021). Also, Kumar et al. (2018) observed that Indian agriculture has the potential to use satellite navigation (SN) which can increase agricultural productivity. The risk of overlapping areas or missing areas is reduced with this technology, as it is a climate-smart approach to dealing with seasonal disasters.

Many obstacles (like soil salinity in dry areas) hinder agricultural output, reducing crop yields (Mohamed et al. 2021). Climate change influences agriculture yield and quality and may increase soil vulnerability to desertification. Global population growth and limited land holdings have prompted researchers to investigate the Internet of Things (IoT), artificial intelligence, machine learning, and robotics for economically viable, ecologically safe, and sustainable agriculture. Experts are now examining the possibility of developing more logical and flexible robotic systems based on external environment reactions. Orchards and horticultural crops such as oranges, strawberries, and tomatoes are already tested with unmanned remotely operated prototypes. Weeding, spraying, and harvesting robots with cameras and global positioning systems (GPS) have been tested. Also, robotic automated systems have been investigated for automatic feeding and cleaning in an indoor animal production system. Aside from existing precision agriculture approaches, current research shows that the deployment of autonomous tractors and robots in the agricultural farm has lowered farm labour and input costs (Jyoti et al. 2020). The IoT connects sensor devices to perform simple functions. Smart agriculture might be beneficial in dry regions to increase agricultural production with minimal inputs. Some of the benefits are as follows:

- More real-time agricultural data.
- Monitoring and controlling agriculture operations remotely.
- Managing water and natural resource.
- Better livestock management.
- Improve agriculture productivity by evaluating soil and crops properties.

Mohd et al. (2014) developed a web-based geospatial decision support system-graphical user interface for paddies called Soil Water Assessment and Management. For this, data on water irrigation requirement, water productivity index, and irrigation efficiency were provided. This technology provides real-time information by visualizing the outcomes. Palombi and Sessa (2013) established climate-smart agriculture (CSA) technique, to address food security, adaptation, and mitigation. In underdeveloped nations, CSA offers a lot of opportunities to increase food security and resilience agricultural system while cutting emissions of greenhouse gas. This is critical in developing nations since agricultural expansion drives economic growth and is most vulnerable to climate change (Mohamed et al. 2021). The European Union stressed the application of agricultural robots, sensor nodes, and UAVs for the collection of quality (high resolution) satellite images that might be incorporated into the smart agriculture initiatives agreed by 24 EU nations in April 2019 (Bacco et al. 2019). With the expansion of sensing systems for data collection, processing, and analysis, the data utilized in agricultural management has grown rapidly. Thus, a cloud server-based technological network necessitated linking all smart network components at faraway places (Mohamed et al. 2021).

### 34.4.3 Robotics in Agricultural Work

Robots are intelligent machine formed by computers, electronics, and mechanical engineering that mimics human work patterns. Crop harvesting and post-harvest procedures are among the applications of agricultural robotics. Robotic technology not only eliminates agricultural labour but also prevents farmers from working in severe situations. Furthermore, agricultural production involves living products (fruit, vegetables, grains, and flowers) that are very sensitive to environmental and physical factors (Jyoti et al. 2020). Produce during and after harvest needs delicate, precise, and frequently complex care to preserve quality across long distances and time. This trait makes machine or automation replacement of human competence difficult. The majority of labour-intensive jobs in fruit, vegetable, and flower cultivation are still done by hand. Manual labour accounts for up to 40% of overall field operations costs (Bechar and Vigneault 2016). Most agricultural activities occur in unstructured settings characterized by frequent changes in time and place. The topography, vegetation, scenery, visibility, light, and other atmospheric variables in the agricultural field are dynamic, ill-defined, and unexpected. This means that the notion of using robots in agriculture must be compatible with current technology and economically viable. In many agricultural unit operations, robotic technology has been used to mimic or emulate conventional agricultural processes, although no commercial robots for complicated agricultural fields are available (Jyoti et al. 2020).

Sensors, end effectors, control systems, manipulators, and power supply comprise a robotic system. End effectors are robotic parts that connect to their arm or appendages and are used to handle, grab, or grasp items. Manipulators are finite non-rigid elements called links. Robotic joints include revolute, cylindrical, planar, spherical, screw, and prismatic joints. The robot work volume is the three-dimensional space where it can sweep its wrist to maximum and lowest reach. Sensors collect data from the environment and turn it into usable form. Sensors have static and dynamic properties. Tactical and wheeled sensors are utilized in robots. Tactical sensors sense physical contact, whereas wheeled sensors monitor motor position or speed. When developing a robotic system, one must consider the influence of power sources on the mechanism, packaging, weight, and size of the system. Generators, hybrids, batteries, solar cells, and fuel cells are widely utilized in robotics. The control system regulates the behaviour of other subsystems and requires data and information about their present and future phases.

Agricultural autonomous robots are designed to perform and take decisions even in an unstructured and changing environment. Creating an autonomous robot is difficult because of the need for real-time sensor control and modelling solution. Agriculture's autonomous robot is divided into subsystems that conduct certain tasks. In addition, these subsystems and gadgets provide direction on handling single or simultaneous multiple unexpected occurrences and also provide autonomy in the system. The system's main purpose is to plant and seed, while the second task is to move about and interact with humans and other robots. The main component of the robot is meant to mimic conventional agricultural unit activities using end effectors and manipulators. The secondary component interacts with the earth to drive the vehicle in the anticipated direction at the optimum speed (Bechar and Vigneault 2016; Jyoti et al. 2020). Autonomous robots that can pick large quantities of crops quicker than human labourers are being employed in agriculture. Examples: Robots (Harvest CROO Robotics 2021) substitutes 30 human employees for harvesting and packaging of strawberries with the capacity of 8 acres/day. In vineyards, photos were captured using drones to assess crop health (Muniasamy 2020). Nishiura et al. (2013) designed a robot with better soft handling and alignment to raise and graft seedlings with 95% success rates. An automated real-time kinematic positioning guided weed-control system was utilized. An intelligent hoe employs visual systems to recognize rows of crops and manoeuvre itself between them (Slaughter et al. 2008). EcoRobotix is a completely autonomous robot that kills weeds in the agricultural field. The system sprayed at the appropriate area with little harm. The robot's environment variables may be changed (EcoRobotix 2019). Utstumo et al. (2018) developed a system to adapt for changes in cultivation techniques, crop rows, track width, and crop height. Robotics decreased manual labour by 50–100 per cent in naturally produced sugar beets and vegetables and pesticide consumption by 75–100 per cent in high value crops. Robotic weeding was created for maize by Zhao et al. (2016). Various researchers have explored the semiautomatic teleportation of an agricultural robotic system for tomato picking, weed control, and spraying to increase performance (Bakker et al. 2010). Robots are automatic systems that conduct very complicated and unstructured tasks in agriculture. Various subsystems are required to complete the job. Unstructured agricultural robotic systems must be designed to maximize productivity and quality of labour. In recent decades, significant improvement has been made.

### 34.4.4 Use of Internet of Things in Agricultural Implements

IoT-based smart farming allows farmers to use smart technology in their fields to decrease energy waste and increase output and productivity. It gives farmers more control and makes conventional agricultural practices outdated. In 2015, Business Insider predicted 30 million IoT devices used in agriculture, and by 2050, IoT-connected farm-generated data will be 4.1 million/day. IoTs help farmers to offer real-time data for improved crop production decisions. A drone used for pesticide spraying saves labour costs in tough places, while soil monitoring increases production. Modern IoT-based irrigation, automation, crop development monitoring and management, pest control, and pest population control are all examples of smart farming. This farming collects, monitors, and controls agricultural data. Machine-generated data from remote sensing, satellites, or unmanned aerial vehicles. Sensors and other smart equipment help the farm measure and record many operations. The data is currently utilized as IoTs and is suitable for computer processing. A traceability system increases consumer trust in agricultural goods. Eco-data may be collected using smart farming's integrated sensors. Smart dairy technologies include automated feeding, management, milking, and daily health maintenance. Precision farming uses IoT to track soil plots, seedlings, and water conditions. Images, sounds, graphical patterns, and wavelengths may be employed in IoT and advanced technical analysis. The applications of IoT in agriculture are represented in Fig. 34.6. Subahi and Bouazza (2020) developed an intelligent system based on IoT for greenhouse temperature management for the preservation of food quality and also for energy saving. The developed system maintains the optimum temperature around which the system regulates. Sagheer et al. (2021) connected sensors, actuators, and other equipment and put them within the greenhouse to test the platform on cucumbers grown on a soilless medium. They tested this technology in a greenhouse used for commercial production to determine the effect on crop output such as yield and quality. They also revealed that the system boosts plant growth and output while saving money on water and electricity. Agriculture equipment manufacturers (CLAAS, John Deere, Mahindra & Mahindra, YANMAR, etc.) have integrated IoTs in their tractors. For example, YANMAR began developing a robot tractor in 2011 and won the Robot Award in 2016.

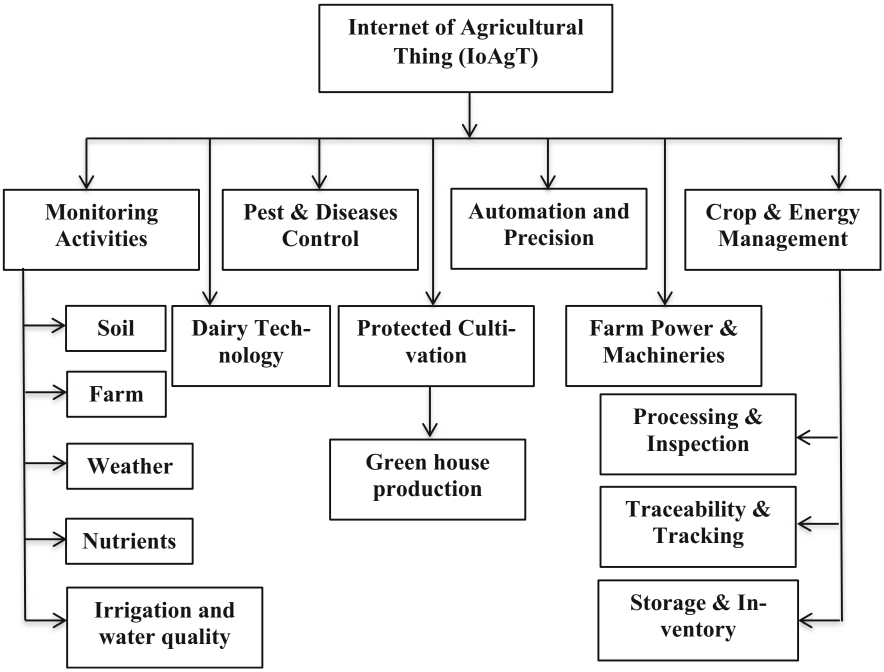

**Fig. 34.6** Applications of IoT in agriculture. Reprint with permission from Santra et al. (2021)

Automated rice transplanters, smart combine harvesters with yield monitoring systems, and smart spraying will transform the way agriculture is done in the future. The Precision Hawk's UAV sensors might offer wind speed and pressure data. Subsoiling may improve soil physiochemical characteristics, soil permeability, crop root system conditions, and yield. Ploughing and sowing need IoT-based agricultural machines. There would be a better technique to obtain perfect seed spacing using mechatronics used in precision planter and seeder. The IoT application in mechatronics will be future agricultural sowing technologies. Australia-AgBot, Europe-CROPS, Finland-Demeter, India-Agribots, Michigan-Hortibot, USA-ISAAC2, and many more nations created prototypes. IoT may be used to handle agricultural supply chain information including crop production, procurement, transportation, storage, and sale. The system delivers agricultural items like fertilizers, insecticides, and seeds to farmers at the correct time and the right price. Concerned about the environment, IoT uses nutrients, water, and insecticides efficiently. Overall, IoT-based machines replace human labour in agricultural monitoring and production (Kushwaha 2019).

Farming also includes livestock monitoring. Traditionally, cattle were fenced in and monitored manually, while modern technology allows for automated tracking and monitoring of livestock. Cattle tracking use GPS with navigation satellites. The application of UAVs makes real-time livestock monitoring simple and economical. Virtual fences may also be created using wireless sensor networks, radio-frequency identification (RFID), and low-power wide-area networks (LPWAN) (Ilyas and Ahmad 2020).

Several researchers already suggested IoT-based geo-fencing and smart agricultural systems. Germani et al. (2019) proposed a long-range LPWAN technology to gather and analyse metrics relevant to cattle health and the environment. An application server processes the data and presents this to the user for further analysis. Simulation results indicated that the suggested architecture covers 7 km$^2$ hilly terrains successfully.

### 34.4.5 Artificial Intelligence

Artificial intelligence (AI) represents human intelligence simulations with machines that are often programmed to think like humans and mimic their behaviour. It also includes computer development or mobile-based intelligent software which is compatible with agricultural user behaviour. In the days to come, most of the agricultural operations will be very much related to AI. This will lead to the development of self-learning algorithms and will help in automation of agricultural practices. Major farm operations including seed bed preparation, sowing/transplanting, weeding, spraying, harvesting, threshing, and transportation will be performed via AI-based applications. Currently, this technology is at an emerging stage, and with time and capital investment, all of the above form operations will be automated, which will increase input utilization efficiency and reduce production costs. Likewise, the Internet of Things (IoT) in agriculture is evolving as new technology includes robotics, unmanned agricultural vehicles (UAV), GPS and remote sensing (RS)-based technologies, and computer-based imaging systems. These technologies comprise different sensors which are readily available in the local market at a lower cost. These sensors will help in the identification and estimation of the soil health conditions, status of ground water levels, NDVI, chlorophyll Index, and crop stress in real time. In India, there are around more than three hundred start-ups in the IoT space, out of which nearly 40–50 are focusing on smart agriculture technology. The adoption and development of IoT-based agricultural devices in India will be a boom for the agricultural industry.

The use of IoT in farm machinery can increase precision and accuracy in farm operations, and ultimately it initiatives smart agriculture with enormous potential with improved technological solutions to the food supply chains and agriculture farming practices. There is also a signal towards better water utilization practices such as sprinkler and drip irrigation systems. In order to reduce the deficit of agricultural production, smart technology needs to be developed in the future; it is very important to keep in mind the small and marginal farmers. At the same time, private and custom hiring organizations can provide support for smart agricultural mechanization. A tractor is one of the major prime movers in agricultural farm operations which requires a skilled person to operate it efficiently. Farming activities are greatly affected by the weather and environment during working hours and nonworking hours. Currently, state-of-the-art technology is equipped with attractive features such as auto-steer, auto-headland turns, auto-implement elevator, skip passing, and safety features such as geo-fence lock and remote engine begin to shut down. The GPS-based auto steer and auto head land turned low a tractor to travel precisely along as straight line and for continuous operation, it can orient itself along with adjacent rows without any giving input steering, respectively. However, an auto implement lift can automatically lift a machine or implement from the base. Tractors modernization through artificial intelligence will lead to higher food production, productivity, higher incomes, and lower health risks for farmers who can meet the growing needs of the growing population.

## 34.5 Conclusions

Day by day, agriculture is getting popularized. Manufacture and distribution of innovative technologies in agricultural farm machines, implements, tools, machines, etc. for every region of the country including arid zone are now fast growing to increase farmer profitability and crop productivity, to help farmers engaged in agriculture and allied sectors, to acquire the means to modernize their farming operations, to provide the necessary custom hiring services for these purposes, to provide technical guidance to farmers and persons belonging to agro-industries, and to enable efficient management of input resources in agriculture. Smart agricultural mechanization is a boon to the agricultural development paradigm that has been widely encouraged to transform agriculture in all countries. The following conclusion can be drawn from reviewing agricultural mechanization.

- Adoption of smart agricultural equipment like zero till drill, no-till drill, combined tillage practice, laser land leveller, and controlled traffic system for seedbed preparation can reduce greenhouse gases, remove carbon from the atmosphere and store it in the soil, and reduce soil disturbance and agricultural inputs.
- Agricultural mechanization in sowing or transplanting is very much required to achieve the desired yield of crops in arid region. Due to labour crisis and human limitations, it is not possible to sow any particular crop in time by manual method. Agricultural mechanization brings timeliness, accuracy and cost-effectiveness in farm operations. It’s also enhance conservation of resources (soil and water) and applied input efficiency.
- There is tremendous research scope on mechanical weeder, inter- and intra-row weeder, and implementing robotic weed control systems for various field crops of arid regions.
- Using real-time clocks, humidity sensors, temperature sensors, mechanized micro-sprinklers, and drip and automated irrigation systems helps reduce water waste, as market demand in our countries is emerging.
- Smart agricultural technologies allow farmers to ensure crop input efficiency by optimum utilization of water or chemical fertilizers which helps to increase in productivity and better yield in terms of product quality.

- Mechanized harvesting and threshing operation needs majorly due to timeliness these operations in order to reduce losses occurring by rodents or climatic changes like rain in the arid region.
- Finally, there is a need to prioritize agricultural mechanization in the arid region and create awareness among the farmers about the techniques of agricultural machinery. A lot of agricultural machinery is being developed, and government subsidy is being given to counter the high cost of agricultural machinery.

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