Santanu Kumar Bal · Joydeep Mukherjee
Burhan Uddin Choudhury
Ashok Kumar Dhawan *Editors*

Advances in Crop Environment Interaction

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Preface

Agriculture is facing multifaceted threats from unpredictable weather variability, frequent drought occurrence, irrigation water scarcity, degradation of soil resources, and environmental health. These stresses result in modification of plant physiology to impart responses to the changing abiotic and biotic environments, only at the cost of decline in the ability of plant productivity. Given these facts, assessing the status of natural resource base and understanding the soil-plant-environmental interaction mechanisms for devising adaptation and mitigation approaches are of great and imminent challenges for all of us. In this context, it is essential to understand potential applications of modern tools and existing coping mechanisms and their integration to develop advanced mitigation strategies. In a broader perspective, the proposed book deals with crop environment interactions in the pretext of changing climatic conditions.

This book tries to bring answers in four major theme areas such as the following:

- Understanding the mechanism of carbon dynamics in soil-plant-environmental continuum, greenhouse gas fluxes in agriculture systems, soil properties influenced by climate change, and carbon sequestration processes
- Mitigation and management of photothermal environment for improving crop productivity, soil health under variable climate, agro-ecosystem evapotranspiration losses through biophysical controls, and heat stress in field crops and its management
- Studying the impact of climate change on biotic environments, insect-pest interaction, manifestation of diseases, and adaptation strategies for island agro-ecosystem
- Innovative approaches for assessing stress impacts in crops such as crop modeling, remote sensing, and spectral stress indices.

This book is a collection of contribution from the authoritative experts in their respective fields, provides a perspective to young researchers and opens up new avenues of work in the respective fields, and will be useful for different stakeholders, including postgraduate students and other academicians as well.

We are extremely thankful to all the contributors for their efforts in providing comprehensive and coherent reviews. We are also thankful to Indian Ecological Society for providing language editing services. We sincerely appreciate Team Springer especially RaagaiPriya ChandraSekaran and Aakanksha Tyagi for providing technical support in this publication.

Hyderabad, India

Santanu Kumar Bal
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Contents

Part I Understanding the Process of Interaction

Part II Making Interaction Favourable Through Management Interventions

Part III Scientific Approaches for Assessing Stress Impacts on Crops

Part IV Stress Impacts on Agricultural Commodities: Few Case Studies

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Part I

Understanding the Process of Interaction

Carbon Dynamics in Soil-Plant-Environment System on Climate Change Perspective: Special Reference to Rice

1

P. Bhattacharyya, P. K. Dash, C. K. Swain, A. K. Nayak, D. Chatterjee,
S. R. Padhy, R. Saha, and D. Barman

Abstract

Carbon is the backbone of life. It is present in the atmosphere, oceans, soils and earth's crust and basically divided into five pools. In this chapter, we have tried to find a link of carbon dynamics in soil-plant-environment system and climate change by keeping in mind the major food crop of India, rice. Climate changes have direct as well as indirect influence on dynamics of soil organic carbon (SOC) and its degradation kinetics that contribute to global warming. In future climatic scenario, there is an opportunity to increase carbon assimilation and carbohydrate accumulation in rice under elevated carbon dioxide (CO_2) environment. Again, temperature moderates the carbohydrate allocation in plant and significantly affects the growth of crop. Moreover, under changing climatic scenario, methane emission may become an important driver because of higher belowground carbon allocation. Therefore, enhancing carbon sequestration, growing of rice with low carbon footprint and soil management for controlling different pools of SOC could be some of the emerging approaches which are discussed thoroughly in this chapter.

Keywords

Climate change · C dynamics · C sequestration · Rice ecosystem

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1.1 Introduction

In last four decades, concern of global carbon (C) cycle increased dramatically because of significant anthropogenic effect on changes in C cycle. Moreover, the topic received higher importance when researches showed that ice core and ocean core sediments have much higher carbon dioxide (CO_2) concentrations than previous times. Spikes also found in core samples CO_2 concentrations which have not been recorded since the last 650,000 years. Global CO_2 concentrations have increased by 37%, from ~275 ppm in the preindustrial era (1000–1750 AD) (Nieder and Benbi 2008) to 395 ppm in 2017. Anthropogenic activities like fossil fuel burning and land use change contributed heavily to C release to the atmosphere. The primary components of ecosystem CO_2 exchange and global C cycle could be listed as oceans, soils, fossil fuels and vegetation. Photosynthesis, respiration, organic C decomposition and mass transfer between air and water are the major pathways through which C is introduced and or removed from atmosphere. Carbon accounts for around 40% of dry biomass in Earth's crust (Houghton 2007) and 0.27% of the mass of elements. In vegetation, forests are one of the biggest reservoir of C as trees hold a larger amount of C per unit area. The oceans have nearly 50 times more C than the atmosphere (approximately 38,000 Pg C; Lal 2003). Majority of those are present in intermediate-deep waters, and around 700–1000 Pg C in the surface ocean have direct contact with atmosphere (Nieder and Benbi 2008). Ocean sediments contained about 6000 Pg of reactive C, important in long-term C fluxes. The primary contributor of excess C in the atmosphere was fossil fuel burning, adding 8.5 Pg C to the cycle every year. Oceans, vegetation and soils were considered as net C sinks with 26.98, 22.22 and 1.59% C sequestration status, respectively. The remaining 50.79% of excess C from fossil fuel burning primarily is responsible for increasing atmospheric C by ~3.2 Pg per year (IPCC 2007, 2014).

On the other hand, soil C represents the largest C reservoir in terrestrial ecosystems (Houghton 2007). It is twice as large as the vegetation C reservoir and has relatively low residence time. Therefore, soil C is becoming the nodal point for scientific research in global C cycle. As annual exchanges of CO_2 from soils to atmosphere are slightly less than that of oceans-atmosphere, slight increases or decreases in net CO_2 exchanges from soils could have a significant effect on atmospheric CO_2 status (Amundson 2001). Soils have huge C sink potential and to mitigate climate change. The predicted C storage by 2050 across the Great Plains region in the central part of the United States is around 2.2–2.7 Pg C. Moreover, it was concluded that C sequestration primarily through increase in soil C and 47% of all land in Great Plains was considered agricultural land.

It is also well recognized that SOC is the single most important indicator of soil quality assessment (Shukla et al. 2006). Soil quality refers to 'the capacity of a soil to function'. In agriculture, it signifies the capacity to sustain and/or enhance biomass production to provide healthy and inexpensive food and fibre to consumers. Therefore, not only the environmental point of view, SOC plays a dominant role in C cycling, soil health and production sustainability.

1.2 Carbon Cycling in Soil, Plant and Environment

Carbon is present in the atmosphere, oceans, soils and Earth's crust. It is present in the systems of plant, animal and any form of the living organism representing different C pools. Any movement of C among these pools is known as a flux. The combination of different C pools connected with the flux directions generates the carbon cycles (Fig. 1.1). The C in the atmosphere (as CO_2) is used by autotrophs in photosynthesis in the presence of sunlight and stabilized it in the form of glucose. This process transfers considerable proportion of C from atmospheric pool to biotic pool. Autotrophs like plants are consumed by animals. Over the time, these plants and animals die, respire and decay; the carbon will be released back to the atmosphere. In the same way many individual carbon cycles are linked among the pools, which integrally form global carbon cycle.

Global C pools are subdivided into five major pools (Fig. 1.2, Lal 2008a, b). Among them, oceanic pool is the largest (estimated as 38,153 Pg), in which surface ocean contributes 900 Pg, intermediate and deep ocean contributes 37,100 Pg, surface sediments contribute 150 Pg and marine biota contributes 3 Pg C. The second largest pool is the geological C pool which is estimated about 4130 Pg. This pool comprises fossil fuels of which 84.99% is coal, 5.57% is oil, 3.39% is gas and 6.05% is others (Lal 2008a, b). However, this C pool is reducing at the rate of 7.0 Pg

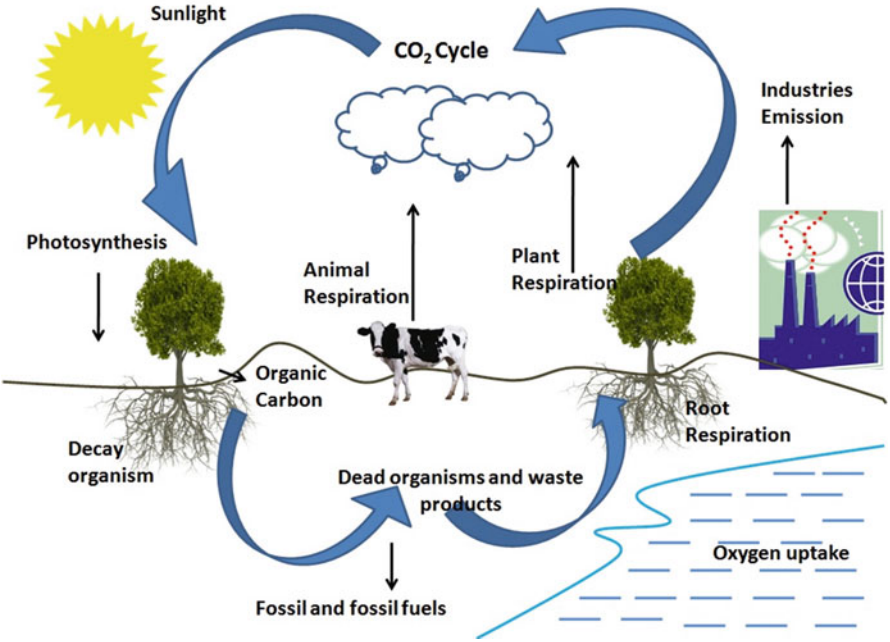

Fig. 1.1 Simplified carbon cycle in soil, plant and atmosphere

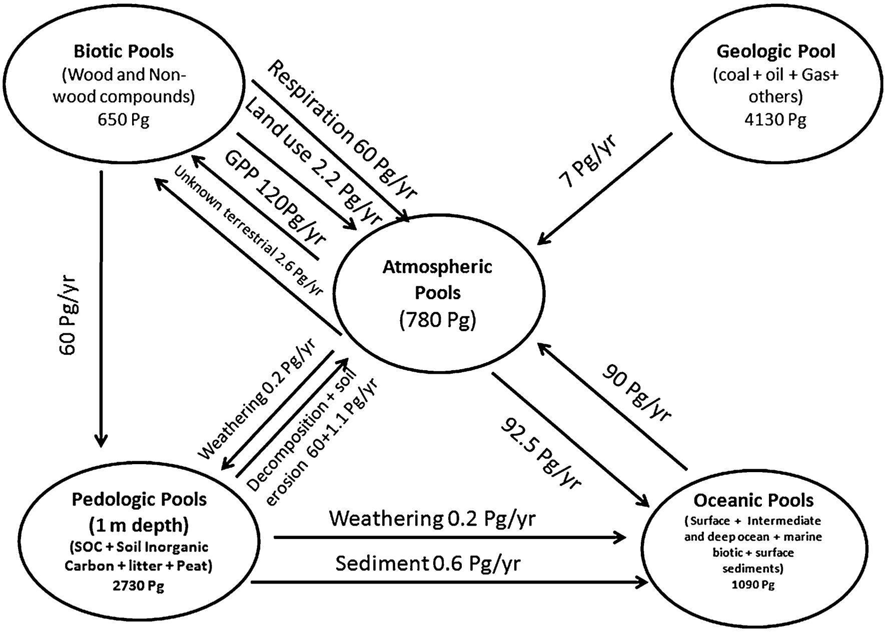

Fig. 1.2 Dynamics of global carbon pools (Note: Source, Lal 2008a, b)

year^{-1} by fossil fuel burning (Bandyopadhyay 2012). Pedologic pool is considered as the third largest, that is, around 2730 Pg up to 1 m depth. This pool includes four components: SOC (1550 Pg), soil inorganic carbon (SIC; 950 Pg), litter (40–80 Pg) and peat (150 Pg, Lal 2008a, b). The largest terrestrial C pool is SOC which plays a nodal role in C cycle and, thus, is considered as the most vital pool for global climate change. Carbon is taken out in the form of CO_2 from the atmosphere by plant during photosynthesis. The C, thus assimilated by plants, is transferred back to soil in the form of dead residues. Recycled residues act a substrate for soil biota which decomposes those and CO_2 and CH_4 become back to atmosphere through respiration. The SIC pool consists of calcite, dolomite and gypsum (carbonates of minerals), elemental C and also primary and secondary carbonates (Bandyopadhyay 2012). Atmospheric pool is the fourth largest pool (780 Pg) increasing at the rate of 4.1 Pg year^{-1}. The biotic pool is the least (500–650 Pg) among the global C pools. The terrestrial C pool is the sum of the pedologic and the biotic C pools. There is more interaction in between the terrestrial and the atmospheric pools (Fig. 1.2). The annual rate of global primary production (GPP) is 120 Pg, while the respiration is 60 Pg of C, land use conversion (1.1–2.2 Pg year^{-1}), decomposition (60 Pg year^{-1}) and soil erosion (1.1 Pg year^{-1}) are responsible for depletion of terrestrial C and at the same time enrichment of the atmospheric C pool. The fossil fuel (coal, oil, gas, etc.) combustion depletes the geologic C pool and enriches the atmospheric pool at the annual rate of 1.5–3.0 Pg carbon. However, the terrestrial C sink is increasing at the rate 2–4 Pg year^{-1} and might increase at 5 Pg year^{-1} by 2050 (Bandyopadhyay 2012).

1.3 Soil Carbon Dynamics

The easy approach to understand soil C dynamics is to understand the pools of organic C on the basis of susceptibility to microbial decomposition and their interactions. All the pools of soil C are present in dynamic equilibrium with different residence time. Their turnover rate depends on their chemical structure, environmental constraints and ambient physical conditions. A flow chart (Fig. 1.3) can precesily represents, such C pools in soil-plant system and their dynamics is presented in Fig. 1.3. Plant residues contain metabolic C, viz., proteins, sugar and starches are readily metabolized by microbes. And structural plant C, mostly present in lignin, cellulose, polyphenols and waxes are resistant to microbial decomposition. In general, an active, slow and passive fraction of organic C together represents total organic C pools in soil.

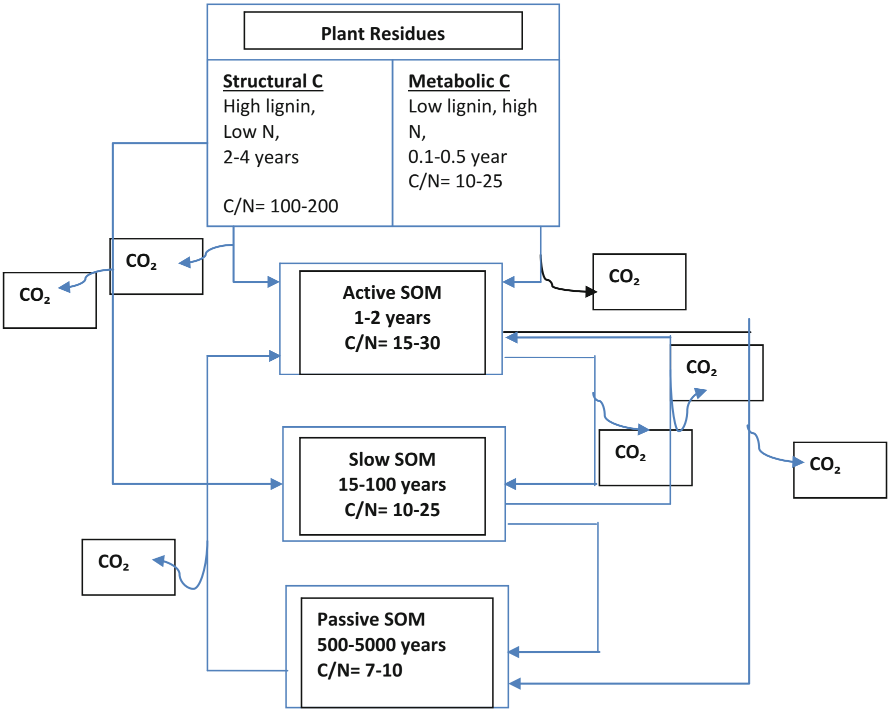

Fig. 1.3 Conceptual model of different pools of SOC and their interactions

1.3.1 Active Fractions/Pools of Soil Organic Carbon

Active pools of SOC represent the materials with a relatively high C/N ratio (~15–30) and short half-lives (few months to few years). Living biomass, fine particles of detritus, polysaccharides and few non-humic substances are the components of this pool. This provides readily available substrates for soil micro-organism and readily mineralizable nitrogen. Beneficial effects of these pools include structural stability of soil which leads to enhancement of water infiltration, easy tilling and reduced erosion. Although this fraction can be readily replenished by addition of organic matter and residues, this could easily be lost also through tillage and intensive cropping. It contributes about 10–20% to total organic C.

1.3.2 Passive Fractions/Pools of Soil Organic Carbon

Passive fraction of SOC represents the stable substances remaining in soil for hundreds to thousands years. The primary components of these fractions are humus, clay-humus complexes, humin and majority of humic acids. These pools accounts for 60–90% of the organic C in majority of soils and decompose very slowly. As an integral part it influences the colloidal properties of soil humus, cation exchange capacity and water holding capacity of soil.

1.3.3 Slow Fractions/Pools of Organic Carbon

Slow fraction of SOC has intermediate properties of active and passive C pools. These pools primarily include slowly decomposable and chemically resistant particles and finely divided plant tissues having high lignin content. Half-lives of these C pools are in decades. The slow fraction is an important source of available plant nutrients. It also provides the food source for steady metabolism of the autochthonous soil microbes.

1.4 Effects of Soil Management on Active and Passive Fraction/Pools of SOC

Soil analytical methods only evaluate chemical or physical fractions of soil organic carbon that approximate the functionally defined fraction/pools: passive, slow and active. Conservation-oriented practices and conservation agriculture facilitate high proportion of active-fraction components as microbial biomass and oxidizable sugars. Despite the analytical difficulties, models which assume the existence of these three pools could able to explain and predict precise changes in SOC levels and associated soil properties. Researches on dynamics of SOC have proved that the different pools of SOC play quite different roles in the system and in C cycle. Soil management practices that cause only small changes in total organic carbon (TOC) often cause rather pronounced alteration in aggregate stability and nitrogen mineralization. This is because of greater sensitivity of active C pools than passive pools in soil to management practices.

1.5 Stability and Degradation Kinetics of Soil Organic Carbon

Stability and decomposition of soil organic matter (SOM) in general and SOC in particular depend primarily on chemical structure of SOC, ambient temperature and moisture conditions. The temperature sensitivity of global C stocks decomposition is the key issue of present day because of its influence on global carbon (C) cycle and climate change feedbacks. Stability of SOC varied among the ecologies. Upland soils having better drainage and aeration facilitate roots and fauna to penetrate deep into lower soil horizons and enhance mixing of mineral particles with SOC favourable for decomposition. Therefore, relatively low C densities are generally observed in upland mineral soils. On the other hand, decomposition rates much slower in wet and peatlands where anaerobic conditions prevail accumulate higher organic C on top of soil layers.

1.6 Drivers of Soil Organic Carbon Decomposition

Balance of inputs and outputs of C in belowground regulates the organic C stocks in soils. Leaf and root detritus are the primary inputs, whereas effluxes of CO_2 from soil surface are the dominant output. Other two important outputs are hydrological leaching of dissolved and particulate C compounds and CH_4 efflux. Rhizosphere respiration and microbial decomposition of SOC represent the majority of CO_2 production from soils. These processes are primarily temperature-dependent. Water status also considerably regulates root respiration and microbial decomposition. Hence, efflux of CO_2 from soils is mostly related to soil temperature and moisture in simulation models. The kinetics of enzymatic reactions and activation energies are also closely related to molecular structure of the SOC and ambient temperature. The temperature sensitivity of decomposition of SOC enhances with increasing molecular complexity of the substrate. Substrate concentrations and affinities of the enzymes to the substrates also modified the rate of reactions.

Soils contain different organic C compounds having their own different inherent kinetic properties. Plants along with detritus that undergo transformations by microbial decomposition produce a wide range of C substrates. Abiotic condensation reactions generate/synthesize new aromatic structures having larger molecular weights, insolubility, which affect the rate and efficacies of enzymatic degradation. Complex molecular structures are characterized by high activation energies, inherently high-temperature sensitivity and low decomposition rates. The ‘intrinsic temperature sensitivity’ of SOC primarily depends on inherent kinetic properties based on molecular structure and ambient temperature of the substrates.

However, physical or chemical exclusion of the organic C substrates from microsites of enzymatic reaction by environmental constraints causing substrate limitation to reaction. In those environmental constraints, the observed response of SOC to temperature is referred to as 'apparent temperature sensitivity', which may be much lower than that of intrinsic temperature sensitivity. Conversely, removal of 'environmental constraint to decomposition' leads to increase in substrate availability that could result in higher apparent temperature sensitivity than intrinsic temperature sensitivity of the substrate temporarily. The environmental constraints include physical, chemical protection, drought, flooding, freezing, etc.

1.6.1 Arrhenius Equation and Michaelis-Menten Kinetics

Temperature coefficient, Q_{10}, refers to the factor at which the rate of reaction increases with 10 °C rise in temperature as given by van't Hoff. Temperature sensitivity of soil respiration also could be explained by that. Relative reaction rates as a function of temperature (Arrhenius equation, Eq. 1.1):

$$k = \mathrm{A} \exp\left(-\mathrm{Ea}/(\mathrm{RT})\right) \tag{1.1}$$

where A is the frequency factor, k is the reaction rate constant, Ea is the activation energy in joules mole^{-1}, R = 8.314 JK^{-1} mol^{-1} gas constant and T is the temperature.

Recalcitrant SOC with complex molecular attributes (adsorbed/complexed SOC) has high activation energies, low decomposition rates and 'inherently' high-temperature sensitivity. Activation energy is a function of ambient temperature and molecular characteristics of the organic C compound (Davidson and Janssens 2006). There is a declining relative increase in the fraction of molecules with sufficient energy to react with increasing temperature, which leads to decrease in the Q_{10} values (Davidson and Janssens 2006; Tjoelker et al. 2001). That is why the highest temperature sensitivities of SOC are observed in colder regions where C stocks are also found to be largest (Post et al. 1982; USDA 2000). The Arrhenius function also shows that the temperature sensitivity of decomposition increases with increasing stability of organic compounds because stabilized substrates are less reactive due to higher activation energies. This means that the stable pool is more temperature-sensitive than the labile pool, which is characterized by low activation energies.

The application of Arrhenius kinetics is limited under conditions of low substrate availability. As described by Michaelis-Menten kinetics (Eq. 1.2), the reaction rates are further modified by substrate concentrations [S] and affinities of the enzymes for the substrates Km:

$$k = \mathrm{Vmax}^{*}\,[\mathrm{S}]/(\mathrm{Km} + [\mathrm{S}]) \tag{1.2}$$

where k is the reaction rate; Vmax is the maximal rate of enzymatic activity at a given temperature; Km is the Michaelis-Menten constant, representing the affinity of enzymes for the substrates expressed as substrate concentration at which the reaction rate equals Vmax/2; and [S] is the substrate availability (substrate concentration at active site of the enzyme).

Substrate availability is directly affected by stabilization of organic compounds (e.g. by interaction with mineral surfaces and metal ions, spatial inaccessibility due to aggregation and hydrophobicity (Sollins et al. 1996; Von Lützow et al. 2006)) or indirectly by external control factors (e.g. water, oxygen and nutrient supply, temperature, pH) that restrict decomposition. *In situ* temperature-insensitive processes such as seasonal litter fall, drying-rewetting and tillage alter the release of easily decomposable substrates.

1.6.2 Cancelling Effects

Michaelis-Menten constant becomes insignificant, and the temperature response of Vmax determines the decomposition rate when substrate is abundant and larger than Km and the temperature does not exceed the optimum temperature. However, Km becomes relevant when substrate availability is low, and the decomposition rate depends on the enzyme as well as on the substrate concentration. Temperature sensitivities of Vmax and Km can neutralize each other (Davidson et al. 2006), because those increase with temperature (Arrhenius 1889). This 'cancelling effect' is significant when substrate concentration is low or lower than Km and if both Km and Vmax have similar temperature sensitivities (Larionova et al. 2007). Respiration is controlled by temperature-sensitive processes which alleviate substrate limitation (e.g. decomposition of recalcitrant SOC pools) and produces available substrate when Vmax and Km cancel each other out.

The cancelling effect could be important for controlling the 'actual' in situ temperature sensitivity in soils as most soils are C-limited (Ekschmitt et al. 2005). However, cancelling effect is generally short-lived as the time delay between Vmax and Km changes is significant.

1.7 Plant Carbon: Partitioning and Allocation

Carbon allocation refers to the distribution of C (photosynthetic assimilates) throughout the plant body. Carbon allocation is an adaptive response to resource stress. The term C partitioning means the division of C (photosynthetic assimilates) into metabolic, structural or storage pools (Caraballo and Earnshaw 2014). In majority of cereals including rice, C partitioning occurs due to loading of sucrose (Suc) into the phloem, delivering it to sink tissues from source tissues (van Bel 2003). The gene 'Suc transporters' (*SUTs*) regulates the loading of sucrose into the phloem (Lalonde et al. 2004; Sauer 2007).

Under the elevated CO_2 environment, there is an increase in C and carbohydrate assimilation within the source, i.e. leaves of C_3 plants (like rice). The changes in CO_2 concentration also lead to changes in the partitioning of biomass between shoot and root. An experiment in open-top chambers showed CO_2 elevation (650 μmol Mol^{-1}) enhanced rice tillering in early vegetative stage, but panicle dry weight $plant^{-1}$ did not change at maturity. Root biomass was improved in elevated CO_2. In elevated CO_2, root/shoot ratio also increased at maturity, signifying higher C allocation to the belowground portion in rice under elevated CO_2 (Weihong and Dali 1998).

Temperature has significant influence on the development and growth of plants by changing the carbohydrate allocation within its different parts. Elevated temperatures significantly decreased carbohydrate assimilation within the source and sink parts of plants (Farrar and Williams 1991). Higher temperature would also trigger sucrose synthesis and decrease carbohydrate accumulation in leaf (Farrar and Williams 1991).

Experiments on the interaction between temperature and CO_2 showed an increase in biomass production in different C_3 grasses and rice at elevated temperatures and CO_2 (Lilley et al. 2001; Morgan et al. 2001; Roy et al. 2012). Moreover, regulation of photosynthesis, P uptake-utilization and sucrose-P synthase in rice were observed under elevated temperature and CO_2 (Sujatha et al. 2008; Bhattacharyya et al. 2013).

1.8 Environment Carbon

The net ecosystem exchange of CO_2 is the balance between fluxes of atmosphere and biosphere. It is associated with photosynthetic assimilation and respiratory effluxes from autotrophs and heterotrophs. The net budget between production and emission determines the nature of the system, whether a sink or a source of CO_2. However, meteorological variability and physiological activities of crop influence the temporal variations of ecosystem CO_2 exchange. Soil respiration is an integrated reporter of ecosystem functioning that represents the major pathway of C emission from terrestrial ecosystem (Mills et al. 2011). Soil respiration is critical as a small change of its rates could significantly regulate atmospheric CO_2 concentrations and soil C sequestration. Soil CO_2 emission integrates the components of soil CO_2 production, rhizospheric respiration as well as soil microbial respiration in soil-plant systems. Variations in soil respiration, i.e. soil CO_2 fluxes, are also influenced by agronomic practices. Agricultural operations affect soil CO_2 flux by altering soil environment like soil pH, temperature, moisture, aeration, C/N ratio of substances, etc. These have significant effect on soil microbial activities and SOC decomposition instrumental for transforming plant-derived C to SOC and CO_2.

1.9 Methane Emissions from Rice Fields

Rice production systems are known to be an important anthropogenic source for CH_4 and contribute around 20 Tg CH_4 annually to global budget (Houghton 1996; IPCC 2014). Intensive rice cultivation in ecologically fragile ecosystem is anticipated to increase CH_4 emission in coming decades. *Rainfed* upland, *rainfed* lowland and irrigated land, representing about 15, 40 and 45% of total rice grown area in our country. Approximately, 48% of Indian rice area is irrigated. Flooded rice fields are the potent sources of CH_4 as well as can also act as sink for C (Bhattacharyya et al. 2014a, b). The source and sink capacity entirely depends on field management practices. Methane is predominantly emitted to the atmosphere through rice plant via aerenchyma pore spaces. Well-oriented aerenchyma tissues provide good conduit to CH_4 emission. Root exudation, nutrient supply and root oxidase activities also regulate the budget of CH_4 in rice field. Submergence/ flooding, methanogenic activities and C status of soils also affect the CH_4 emission from rice production systems.

1.10 Carbon Sequestration

Soil C sequestration primarily refers to accumulation/ transferring of atmospheric CO_2 into soil C pool with high residence time and storing it through judicious land management and cropping practices. The process of C sequestration involved both organic and inorganic C. Broadly, this is the process of transferring CO_2 from the atmosphere into the soil through crop residues, organic solids and other means in such a form so that it is not lost in short period of time.

1.11 Mechanism of Carbon Sequestration

1.11.1 Physical

The organic matter per se carbon may be protected from enzymatic degradation by sequestration within mineral mesopores (2–50 nm diameter), which is postulated under 'mesopore protection hypothesis' (Wang et al. 2003; Mayer et al. 2004). The tortuous porosity of mesopore hinders the oxygen to reach to the stored C, which may involve in low C accessibility to microorganisms and reduce microbial respiration.

Some short-range ordered minerals like allophane also protect C physically which is attributed to its peculiar structure analogous to a natural gel (Woignier et al. 2006). In the aggregates, SOC is also protected in microaggregates and mesoaggregates. Sometimes addition of OM decreases in permeability and few pore spaces being occupied by OM itself. Those subsequently facilitate the creation of inaccessible microporosity (Curry et al. 2007). Those physical protections of SOC prevent easy decomposition by inhibiting enzymatic breakdown (Rothman and Forney 2007).

1.11.2 Chemical

Chemical stabilization of SOC is related to the formation of organo-mineral (MIN-SOM) complexes (Basile-Doelsch et al. 2005; Mikutta et al. 2005; Broquen et al. 2005; Wiseman and Püttmann 2006) and organometallic (Al/Fe-SOM) complexes formed with aluminium and iron ions (Wiseman and Püttmann 2006; Egli et al. 2008; Chatterjee et al. 2013). Sorption plays an important role in SOC protection (Wiseman and Püttmann 2006). The organo-mineral complex is produced by the large number of valence-unsatisfied hydroxyl groups of these Al, Si and Fe hydroxides, which have the ability to adsorb ions and compounds of opposite charge specifically (Shoji et al. 1993; Mikutta et al. 2005), and the mechanism is the linking of SOM to clay particle through polyvalent cations and represented as [(Clay–P–SOM)x]y, where x and y are whole integers depending upon the size of primary clay particles (Manjaiah et al. 2010). Some other mechanisms like ligand exchange, coulombic attraction, van der Waals forces, polyvalent cation bridging with or without mediation by hydration water or hydrogen bonding, water bridging, etc. are also involved (Theng et al. 1986; Theng and Tate 1989). Both organo-mineral and organometallic complexes are very stable C reservoirs. This is primarily due to the toxic effect that aluminium has on soil microbes and also allow limited accessibility to enzymes, that protects the organic compounds from mineralization, by making the mean residence time of organic C very high (Basile-Doelsch et al. 2005).

1.12 Soil Processes Affecting C Sequestration

1.12.1 Aggregation

An aggregate consists of an assemblage of a number of primary particles (sand, silt and clay) into a secondary unit. Soil aggregates are formed by the combination of mineral particles with either organic or inorganic binding agents or both, which are the secondary soil particles (Bronick and Lal 2005). The formation of soil aggregates involves several factors such as microorganisms, vegetation, soil fauna, clay-clay interactions, clay-organic interaction and impact of cations (Baver and Gardner 1972). Stable microaggregates increased by the production of organo-mineral complexes, which encapsulates C and protects it against microbial activities (Kumar et al. 2013).

1.12.2 Secondary Carbonates Formation

In this process, the atmospheric CO_2 is chemically transformed into mineral carbonates like $CaCO_3$, $MgCO_3$ and other minerals which are geologically and thermodynamically stable (Lal 2008a, b). This process involved two stages, i.e. scrubbing and mineral carbonation. In scrubbing process, first CO_2 is absorbed in an amine or carbonate solvent. Then pure CO_2 gas is re-precipitated through

Table 1.1 Estimate of C sequestration through formation of secondary carbonates

Eco region	Land area (billion ha)	Potential rate (kg ha^{-1} year^{-1})	Total potential (Pg C year^{-1})
Arid	2.55	0–1	0–0.0026
Semiarid	2.31	3–114	0.0069–0.2633
Subhumid	1.30	1–124	0.0013–0.1599

mineral carbonation through heating the CO_2-rich amine. Finally stable rock carbonates are formed in which CO_2 is sequestered forever. For example, the formation of magnesite ($MgCO_3$), olivine (Mg_2SiO_4) and serpentine ($Mg_3Si_2O_5(OH)_4$) through the aqueous mineral carbonation reactions is as follows (Gerdemann et al. 2003). An estimate of C sequestration through formation of secondary carbonates is given in Table 1.1 (Rosenberg and Izaurralde 2013).

1.12.3 Humification

Humification process refers to the alteration of residues of plant and animal origin into a stable and recalcitrant end product in the form of complex humic substance. Carbon is an important building block needed for this conversion, but simultaneously this process requires equivalent quantity of N, P, K, S and other nutrients. To sequester 10,000 kg of C in humus, there is a requirement of 833 kg of N, 200 kg of P and 143 kg of S (Himes 1998). Therefore, quality and fertility of soil and the interaction of soil with C inputs may strongly control the sequestration of C (Canadell et al. 1996). Thus, the application of organic manure and the land use system determine the amount of C stored in soils and the rate at which this storage could happen. If the applied organic matter contains less N, P and S per molecule of C, i.e. much higher C:N:P:S ratio, then there will be the requirement of additional mineral fertilizers which allow the formation of new fine fraction of soil organic matter that improves the humification efficiency of soil organic matter (Kirkby et al. 2013, 2014).

1.12.4 Translocation and Transportation

Translocation of eroded soil organic matter into the subsoil may promote carbon sequestration. Transport of soil organic matter-enriched sediments into protected areas of the landscape (like subsoil) and to depression sites and/or aquatic ecosystems protects the loss of carbon. Actually, a part of the translocated soil organic matter is buried and the rest is redistributed (Smith et al. 2001), which emitted into the atmosphere either as CO_2 through mineralization or as CH_4 by the process of methanogenesis (Alemu 2014). The deposition and burial of translocated soil organic matter are estimated to be 0.4–0.6 Gt C per year compared with 0.8–1.2 Gt C per year emitted into the atmosphere (Lal 2003).

1.12.5 Mineralization

Mineralization is a process in which the fixed atmospheric C in the form of organic matter is transformed into inorganic compounds mediated by the microorganism., hence reduces the chances of sequestrating more C in soil. However, this process should not be prevented artificially for reducing CO_2 emission in the atmosphere, because artificial limitation of the organic matter mineralization may lead to a shortage of nutrients and, thus, may decline the crop yield. Consequently, the photosynthetic binding of CO_2 may diminish (Janzen 2006). Therefore, a strategy aimed at increasing the stable pool of soil organic C seems to be more appropriate than a strategy aimed at limiting the C mineralization (Paustian et al. 2000).

1.12.6 Soil Erosion

Soil erosion negatively affects the carbon sequestration process. Through soil erosion induced processes, about 1.14 Pg of C are emitted annually into the atmosphere (Lal 2001). Soil erosion affects the C pool and fluxes because of several processes. It includes soil aggregate breakdown, exposure of C to climatic elements, organic matter mineralization in both disrupted aggregates and redistributed soil, transport of SOC-rich sediments into protected areas of the landscape and C sequestration with sediments in depositional sites as well as aquatic ecosystems (Alemu 2014) (Fig. 1.4).

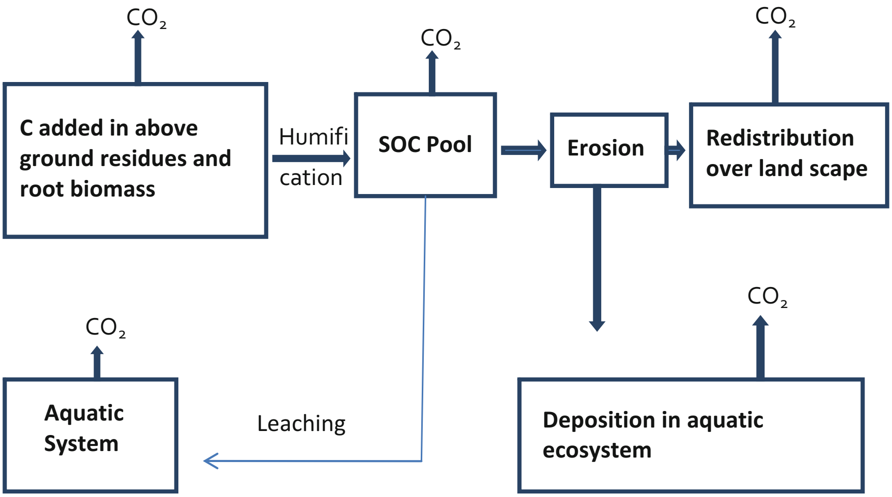

Fig. 1.4 Various soil mechanisms affecting carbon sequestration

1.13 Management for Carbon Sequestration

1.13.1 Biochar

An enormous amount of crop residues are being produced from the agricultural sector. The global estimate of crop residue production for cereal crops and 27 food crops are 2.8 and 3.8 Gt per year, respectively. In India, agro-residues are produced in a tune of about 435.98 million tonnes annually, among which 313.62 mt are in excess. However, those are partially utilized for various reasons (Murali et al. 2010) and 16% is burned (Streets et al. 2003). Accumulating residues can cause considerable crop management problems, and burning of these huge amounts of residues can even cause global warming. CO_2 is one of the most important greenhouse gases and as a result of biomass burning immediately releases CO_2 from nearly all carbon stored in the biomass. Increasing trend in environmental degradation is the concern, and at the same time, search for alternatives to crop residue burning is the need of the hour. Biochar is one of the solutions of this issue. Application of biochar in agriculture is a potential tool for C sequestration and sustainable soil management. In this process the biomass is transferred to an inactive C pool in biochar and redistributed to agricultural fields resulting in C sequestration, and at the same time agricultural productivity as well as environmental quality can be sustained and improved.

Biochar is rich in C, fine-grained porous products produced by thermochemical conversion process (pyrolysis) from the plant biomass at low temperatures (~350–600 °C) in an environment with absence of oxygen (Amonette and Joseph 2009). Biochar is also rich with hydrogen (H), oxygen (O), nitrogen (N), sulphur (S) and ash in a different proportion (Masek 2009). Due to the physical characteristics/quality of biochar like high porous structure, more surface area and higher water retention capacity, soil scientists recommend it as an important soil amendment.

In addition to improvement of soil physical quality, it has high carbon sequestration potential, nearly 30–40% more than non-biochar materials (Lehmann and Rondon 2005). During the process of conversion of biomass to biochar, about 50% C contained in biomass is lost, leaving the stable biochar carbon, whereas almost 80–90% C content in non-biochar material in soils is lost in a period of 5–10 years depending on the quality of biomass and its exposure to the environment (Lehmann et al. 2006). However, non-judicious application of biochar in soils to increase terrestrial carbon sink may reduce soil productivity. Therefore application rate of biochar to get optimum crop response needs to be evaluated for long-term carbon sequestration management strategy. It has been observed that there is a straightforward relationship between crop yields and addition of biochar to the soil up to 50 MgC ha^{-1}, whereas the performance of crops may reduce at very high applications. But in most soil ecosystems, the performance of numerous plant species showed increasing trend even with 140 MgC ha^{-1} (Lehmann and Rondon 2005).

1.13.2 Conservation Agriculture

Conservation agriculture (CA) is an important model of sustainable agriculture which leads to profitable food production. This is also protecting and restoring the natural resources. Farmers are benefited with this technology because it increases crop yields and reduces production costs. It also has positive impacts on environment as well as society by enhancing food security, increasing soil fertility, improving water quality, reducing soil erosion and also helps in mitigation of climate change by increasing carbon sequestration. Conservation agriculture is a sustainable option for intensification as well as environmental protection as it is, in one hand less sensitive to climate and on the other provides resilience to the system.

Conservation agriculture is based on healthy functioning of the whole agro-ecosystem with a maximum attention and focus on the soil. The soil is not only a physical support to roots and plants but also a living entity with its physical, chemical and biological characteristics. The focus of CA is determinants of sustained productivity, which embraces the nutrient contents of the soil as well as its biological and structural status.

The main paradigm of CA is to convert an undisturbed or unhealthy soil to develop a fertile soil and produce healthier plants.

1.13.3 Principles of Conservation Agriculture

Conservation agriculture is a system which refers to reduce soil tilling as well as retaining the crop residues on the soil surface and maintaining the crop rotation.

The key elements which characterize CA include:

(a) Zero/minimal soil disturbance (no-tillage and direct sowing and direct placing of planting materials to soil)
(b) Permanent soil covers either by crop residues or by cover crops
(c) Crop diversification in sequence/associations through rotations

Conservation agriculture principles are converting a low-yielding, dry, rainfed conditions to high-yielding, irrigated conditions in a wide range of crop production systems. It also sustain biodiversity and natural biological processes both in above- and belowground soil surfaces. External inputs such as agrochemicals and plant nutrients of minerals or organic origin are applied without soil interventions such as mechanical tillage which are reduced to an absolute minimum or avoided optimally. In this way the soil qualities do not interfere with, or disrupt, the biological processes. CA facilitates good agronomy, such as timely operations, and improves overall land husbandry for rainfed and irrigated production. At the same time, CA complies with the generally accepted ideas of sustainability. The use of chemical fertilizer and pesticides, including herbicides, is also reduced in the long-term application. Depending on the agroecological location and management practices, it further helps in C sequestration in soil ranging from 0.2 to 1.0 t ha^{-1} $year^{-1}$. About 50% labour requirements are generally reduced which helps the farmers to save time, fuel and machinery costs.

1.13.4 Cover Crop and Residue Management

In organic agriculture, cover crops are incorporated by tillage. Incorporating of legumes enhanced productivity in wet season, and surface mulch in dry season was found effective. Mulching is helpful for in situ moisture conservation, weed suppression and nutrients mobilization both in organic and integrated nutrients management practices.

Crop residues directly effect on the evaporation of the water content from the soil surface and also the amount of water infiltrates into the soil. The organic residues incorporation significantly increases the crop yield with improvement in soil physical properties. It was reported that incorporation of locally available organic residues (*Ambrosia sp.*) continuously for 5 years in puddled rice could increase SOC by 21.1%. Apart from this it also increases the stability of microaggregates, moisture retention capacity and infiltration rate of the soil by 82.5, 10 and 31.3%, respectively (Saha and Mishra 2009).

1.14 Carbon Dynamics and Climate Change Feedback

Climate change affects SOC dynamics as well as its decomposition kinetics. Soil organic carbon decomposition that provide a feedback to the gaseous-C concentrations to the atmosphere contributes to the global warming. There are both direct and indirect effects of carbon dynamics to climate change feedback. Direct effects include temperature-mediated soil respiration, SOC decomposition leading to gaseous C emission, changes in precipitation and extreme climatic events.

As SOC decomposition rates and soil respiration are more sensitive to temperature than primary production it is predicted that climate change would increase the net transfer of C from soil to atmosphere, thereby creating a positive feedback to climate change. Growing stress tolerance species also contribute to a positive feedback to climate change. Increase of primary production (higher photosynthesis) and reduction of the length of growing season cause negative feedback to climate change by reducing the CO_2 emission to the atmosphere and absorbing more CO_2 from the atmosphere. The indirect effects which include positive feedbacks are (i) percolation and runoff losses of dissolved organic carbon (DOC) and (ii) higher root exudation that causes faster SOC decomposition through ‘priming effect’ and promotes methanogenesis and hence enhances the C losses from soil as methane. The indirect negative feedbacks include (i) increasing plant-microbial competition for nitrogen (N) that causes ecosystem C accumulation, (ii) increasing growth of mycorrhizal fungi causing C accumulation and (iii) stimulation of microbial biomass and immobilization of soil N causing limitation of N availability to plant and hence accumulation of C in soil. Another indirect effect on climate change (both positive and negative feedbacks) is through shifts in the functional composition and diversity of microbes and vegetation which occurs over longer time scales of decades and centuries.

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Monitoring Greenhouse Gas Fluxes in Agro-ecosystems

2

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Abstract

Monitoring net exchange fluxes of greenhouse gases (GHGs) over agricultural fields is done either by chamber-based measurement approaches or using micrometeorological techniques. Chamber-based methods provide point-based measurements, but those can be customized and implemented at low costs in the field. Micrometeorological techniques, on the other hand, provide area-integrated measurement of gas exchanges without altering the natural canopy microclimate condition. With recent advances in instrumentation, fluxes can be measured at a very high temporal frequency of the order of hours to minutes. However, instrumentation is costly, often requires power supply and a homogeneous crop cover of a certain minimum area and knowledge of micrometeorology on the part of the user for a comprehensive GHG budgeting. Eddy covariance (EC) is regarded as the most robust micrometeorological technique which provides the most direct measurement of energy and GHG fluxes. This chapter mainly deals with CO_2 flux measurement using eddy covariance technique. Guidance on various measurement protocols such as site selection, sensor configuration, and its orientation is provided. Sources of error in the eddy covariance data, data screening steps and various gap-filling measures such as mean diurnal variations, linear and non-linear regressions and look-up tables and flux validation have been addressed. It further includes a brief review of GHG exchange dynamics over agricultural landscapes, emerging challenges and case study of flux monitoring in three different crop ecosystems of semiarid Deccan plateau of peninsular India.

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Greenhouse gas · Agro-ecosystem · Flux · Instrumentation

2.1 Introduction

Since the beginning of the industrial revolution around 1750 AD, atmospheric concentrations of various greenhouse gases have been rising due to anthropogenic activities. In 2011 the concentrations of three key greenhouse gases, viz. carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), were 391 ppm, 1803 ppb and 324 ppb having exceeded the pre-industrial levels by about 40, 150 and 20%, respectively (Hartmann et al. 2013). CO_2 is the most important GHG as nearly 72% of total emission is CO_2. The continuous rise in atmospheric CO_2 concentrations is occurring as a result of imbalance between the rate of emission of CO_2 and the rate of removal of CO_2 from the atmosphere by vegetation biosphere and oceanic sinks. The alarming trend in the concentration of CO_2 and other GHGs has given rise to the most prominent global environmental issue of today's earth, i.e. global warming, as these gases absorb the outgoing thermal radiation from the earth's surface and reradiate it back to the surface, thereby causing an increase in the ambient temperature. Global warming, in turn, has also triggered changes in the behaviour of many climatic parameters and occurrence of extreme events, more prominently in the last few decades. In view of direct correlation of GHG concentration with global warming and climate change, proper monitoring of GHG emissions from the earth's surface is required. A thorough understanding of various processes that lead to net gas exchange from earth's surface, quantification of spatio-temporal dynamics of GHGs and assessing source or sink potential of various ecosystems under varied climatic conditions form the basis for developing GHG mitigation strategies from terrestrial ecosystems.

Managed ecosystems such as agriculture play equally important role like the natural terrestrial ecosystems (e.g. forest and grasslands) and may contribute significantly to regional carbon budget where crops are dominant. Furthermore, agricultural lands are prone to wider variations in the gas exchange rates compared to natural ecosystems and hence require proper monitoring. Several studies have been carried out to quantify gas exchanges and net emission of GHGs from agriculture. It is estimated that agriculture contributes around 10–15% of total anthropogenic emissions globally (IPCC 2007). However, because of differences in methodologies used for such quantifications, there are a lot of uncertainty in the estimates and often intercomparison among sites, crops or experiments becomes difficult. Hence, for maintaining uniformity and robustness in the datasets, there is a need to follow some standard methodology.

GHG exchange studies are done either by chamber-based measurement approaches or micrometeorological techniques. Chamber-based methods can be implemented at low costs but become cumbersome for large-area measurements as sample size increases. Micrometeorological techniques are more robust having specific advantages over point-based chamber methods as the former provide area-integrated measurement of gas exchanges without altering the natural canopy micro-climate condition. With recent advances in instrumentation, such measurements are done on a continuous basis and at a very high temporal frequency. However, instrumentation is costly and often requires power supply, a minimum footprint area and knowledge of micrometeorology on the part of user for proper sensor orientation, data processing and final flux computation. Of the various micrometeorological methods, eddy covariance technique has been widely accepted as the standard, and it is becoming the preferred choice in long-term flux monitoring programmes worldwide (Aubinet et al. 2000; Baldocchi et al. 2001). This chapter provides an overview of various approaches with major focus on implementation of eddy covariance system-based monitoring of GHGs in agro-ecosystems. In doing so, the key issues such as instrument setup, installation, data quality and processing issues have been dealt upon. At the end, the chapter includes flux measurement results in terms of major GHGs such as CO_2, CH_4 and N_2O for various crop ecosystems and some India-specific case studies.

2.2 Techniques for GHG Measurement

Within the crop field, a lot of spatial variability can be found which causes both spatial and temporal variability in GHG fluxes. The variability could arise due to differences in bulk density resulting from use of machinery, inherent texture, management (rows, interrow spaces, cropping, non-uniform distribution of fertilizers and manures), soil temperature (canopy shading), soil moisture (due to groundwater depth, lateral seepage, fissure, texture), organic carbon (non-homogenous distribution of crop residues), soil depth and rooting depth and distribution all of which affect soil microbial population and activity. The approaches for measurement of greenhouse gas fluxes between agro-ecosystems and the atmosphere can broadly be classified into two groups, viz. chamber-based methods and micrometeorological methods. However, for a more comprehensive study, a combination of the two aforesaid approaches should be followed.

2.2.1 Chamber Methods

Chamber-based techniques are essentially point measurements. In these, gas samples from within the enclosures or chambers are collected either manually or in an automated mode. The samples are then analysed in laboratory using gas chromatography technique. Spatial variability in the measured GHG fluxes is a major drawback of the chamber approach, particularly for highly diverse smallholding farm systems as can be found in India. Another drawback is that imposition of artificial chambers may disturb the microclimate such as creating significant difference with the ambient environment in terms of temperature and obstruction in natural wind flow, thereby introducing errors in the measured fluxes. Also, to adequately represent the temporal variability or when day-night trend is to be monitored, chamber method becomes cumbersome and often impractical due to the requirement of more number of trained laboratory staff, instruments and chemicals.

2.2.2 Micrometeorological Methods

Micrometeorological methods can broadly be divided into two categories, viz. vertical flux-profile or flux-gradient and eddy covariance techniques. In contrast to chamber techniques, micrometeorological methods offer to provide high-frequency temporal measurement integrated over a large area and without disturbing the natural microclimate of the area. Of late, with the advent of state-of-the-art sensor technology, automation and highly efficient computational tools, eddy covariance techniques have emerged as the most preferred choice of the contemporary research community for GHG monitoring at ecosystem scale (Aubinet et al. 2000; Baldocchi et al. 2001). However, uniform terminology and a single methodology are still being developed for the eddy covariance method, and much of the effort in this direction is being done by various flux networks across the world such as FLUXNET, ICOS and NEON. The following sub-sections deal with various micrometeorological techniques with special emphasis on the eddy covariance technique.

2.2.2.1 Vertical Gradient Methods

These are mainly of two types, viz. the aerodynamic gradient method and Bowen ratio-energy balance (BREB) method. Both of these use measured gradients of atmospheric variables in the determination of fluxes. In each case, a time-averaged estimate is produced, representing typically a half-hourly or hourly average flux. The aerodynamic gradient method utilizes the near surface logarithmic wind profile, while the BREB method (Bowen 1926) assumes short-term closure of the surface energy balance and does not require explicit calculation of a turbulence coefficient. The BREB method is a low-cost technique, does not require power supply and is primarily designed for measuring energy fluxes, i.e. latent and sensible heat, rather than measuring trace gas fluxes. It requires more assumptions to be fulfilled than the aerodynamic gradient method. The aerodynamic gradient method is more suited for barren or low-vegetation surface and is difficult to apply over complex vegetation due to the fact that GHG concentration gradient such as that of CO_2 is often small in such ecosystems (Raupach and Legg 1984; Monji 2003).

2.2.2.2 Eddy Covariance Methods

The majority of transport between the soil or vegetation surface and atmosphere takes place mainly through the process of turbulence (instantaneous fluctuations in the vertical wind speed from its mean value) and only slightly through the process of

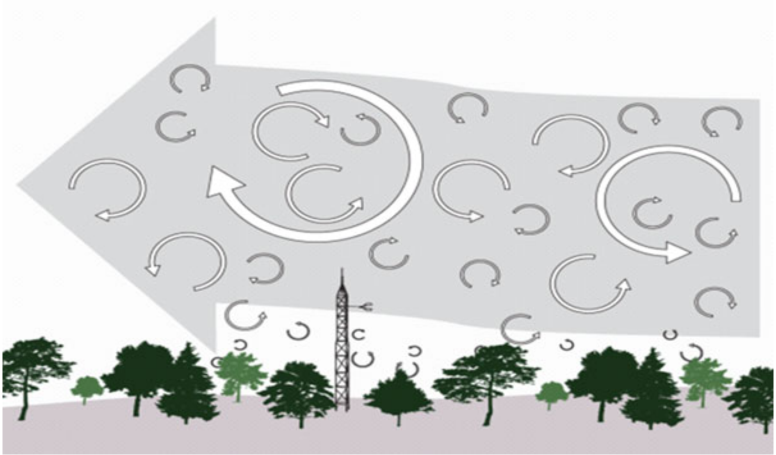

Fig. 2.1 Concept of eddy turbulence exchange in a wind flow

diffusion caused by local gradients such as concentration gradients of CO_2 or temperature. Wind flow at any time can be pictured as a horizontal flow of numerous three-dimensional rotating eddies (Fig. 2.1) which bring with them different surface or environmental properties such as temperature, humidity and partial gas concentration. An eddy covariance (EC) system essentially consists of fast response sensors that are capable of measuring the vertical wind speed and simultaneously some other properties of the turbulent eddies, as stated above, at a very high frequency (e.g. 10 Hz or more). The method of measurement is mathematically complex and requires a lot of care in setting up and processing the data.

The name eddy covariance (EC) has its origin in the fact that such system measures statistical covariance between the vertical wind speed and an atmospheric property whose flux (the quantity of an entity that moves through a unit area per unit time) is to be determined within the atmospheric boundary layer. The mean vertical flux density of a gas (Fz) is approximately equal to mean air density (α) multiplied by the mean covariance between the instantaneous deviations of vertical wind speed (w) and mixing ratio (c) of the gas under consideration (i.e. ratio of the molecular weight of the gas divided by the weight of dry air) for a given time period such as 30 min or 1 h (Baldocchi 2003).

$$\mathrm{Fz} = \bar{a}^{*}\,\overline{w'c'}$$

In the above equation, the over bars denote time averaging and the primes represent fluctuations from average value. In a similar manner, other eddy/turbulent fluxes such as sensible and latent heat fluxes can also be computed. For example, in calculation of sensible heat flux, temperature and, for latent heat flux, water vapour density have to be considered instead of mixing ratio, while other terms remain the same, and conversion to energy units is accomplished by including the specific heat term. Each flux is associated with a sign. Unless otherwise mentioned, all through this chapter, positive flux shall indicate a net transfer into the atmosphere, whereas a negative sign is used to indicate net downward movement, i.e. towards the vegetation/soil surface from the atmosphere. The above sign convention is followed by the atmospheric physicists and micrometeorologists and exactly opposite sign convention is also used by some research groups.

Some other micrometeorological methods which are close variants of the eddy covariance technique can be found in literature. Those were developed by the researchers mainly under situations when there were limitations of response time of sonic anemometers and trace gas analysers. For example, disjunct EC technique could be used to limit the analysis to an equally spaced subsample of eddies when trace gas analysers have a response time of the order of tens of seconds (Lenschow et al. 1994). Watanabe et al. (2000) used bandpass EC technique to correct the high-frequency losses which were due to the slow instrumental response, tube attenuation in closed-path EC system and the sensor separation between sonic anemometer and gas analyser. Eddy accumulation or relaxed eddy accumulation techniques (Desjardins 1977; Businger and Oncley 1990; MacPherson and Desjardins 1991) are based on fast conditional sampling of upward and downward moving eddies using the ultrasonic anemometer vertical velocity signal. The air is sampled at a constant flow rate and stored in two separate reservoirs, one for the updrafts and another for the downdrafts. The covariance is proportional to the difference of the mean trace gas mixing ratio associated with updrafts and downdrafts and to the standard deviation of the vertical wind velocity. Sometimes, a dead band can be imposed on vertical velocity, within which no conditional sampling is performed in order to enlarge the trace gas concentration difference between updrafts and downdrafts (Pattey and Desjardins 1993). A comparison of fluxes measured by the band pass and relaxed eddy accumulation techniques with that of eddy covariance techniques showed reasonably good agreement between them (Hamotani et al. 1996; Watanabe et al. 2000).

2.3 Designing Experimental Setup with EC System

To obtain best measurements using the eddy covariance technique, proper site selection and experiment setup are the foremost requirement. While installing a flux monitoring station due considerations should be given on the following aspects:

2.3.1 Site Characteristics

Like any other micrometeorological methods, EC method too ideally requires a flat terrain, spread over a wide area around the flux tower and homogenous in terms of land use, crop management and soil characteristics. The site should be characterized with respect to topography or slope percentage, seasonal wind speed and direction pattern (wind roses) and rainfall. Several footprint models (Hsieh and Katul 2000;

Kormann and Meixner 2001; Kljun et al. 2004) are available in literature wherein wind and surface roughness information could be fed to know the plausible footprint (the area that contributes to the total measured flux) and fetch (the upwind distance which is required for the wind to come into equilibrium with the underlying vegetation) under varied meteorological conditions and in season vegetation dynamics. Empirical observations suggest that even for the smallest type of crops, a footprint area of more than 1 ha size would be required for EC method to use. Tall features such as buildings, trees etc. should not be present in the vicinity of the flux tower as it may obstruct the natural wind flow in the fetch.

If the area receives low amount of rainfall, then open-path eddy covariance system should be used. For high-rainfall areas, closed-path eddy covariance system serves the purpose best. It should also be kept in mind that closed-path system and some trace gas analysers (e.g. for N_2O) require more power; hence provision of grid power supply should be there in the location.

2.3.2 Positioning of the Flux Tower

At the measurement site, the eddy covariance sensors (those could be put on a tower or heavy duty tripod) should be positioned in such a way that it gets the maximum possible fetch in the upwind direction. It has been observed that most of the contribution in total measured flux at the tower usually comes, not from underneath the tower or far away from it, but rather from somewhere in between. Often it is encountered that the site which is available for flux monitoring study does not have a wide homogeneous area rather appear checkerboard type owing to small farm holdings where crops and management vary or may require evaluating a number of experiments within a limited land area. An example of how best the eddy covariance methodology could be used under such situation has been discussed elaborately by Pattey et al. (2006) and Burba (2013).

2.3.3 Height of Sensor Placement

The depth of air within the atmospheric boundary layer over a vegetation surface can be divided into several strata (Fig. 2.2), viz. roughness sublayer, inertial sublayer and mixed layer. The boundary and depth of each of these strata depend on the vegetation height, topography of the area and the prevailing meteorological conditions. For routine flux monitoring, the measurement apparatus should be placed at such a height that it always remains within the inertial sublayer. When there is a limitation of fetch, the above sensors should be placed near to the boundary with roughness sublayer than further away. A general rule of thumb is that the measurement height should be 100 times smaller than the desired fetch (i.e. height/fetch ratio = 1:100) to avoid sampling outside the area of interest. However, experimental data suggests that the actual height/fetch ratio under a given condition may be as low as around 1:25 (Munro and Oke 1975) to as high as around 1:500 (Burba 2013).

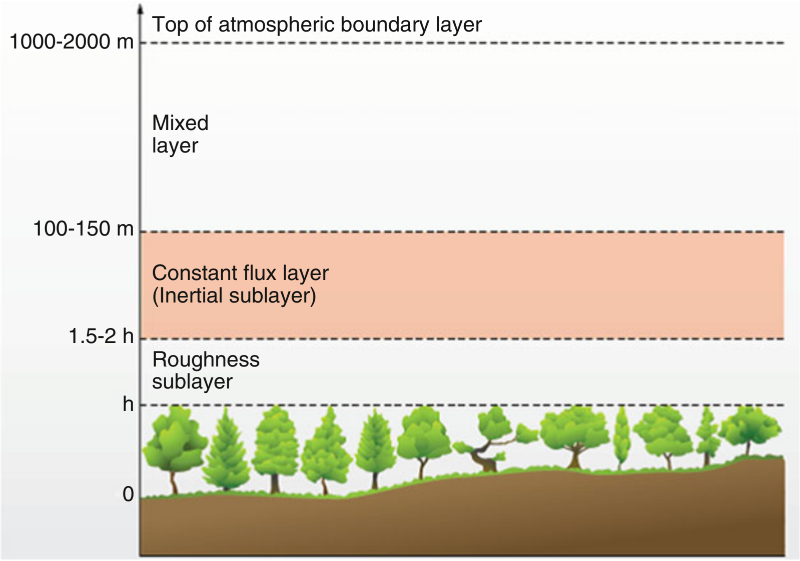

Fig. 2.2 Layers of atmosphere above a vegetative surface. (*Source:* Stull 1988; Oke 2007)

For agricultural crops (heights <3 m), it may be advised to position the flux sensors at about 1–1.5 m above the top of the canopy. For example, if the canopy height is 0.5 m, the flux sensors should be placed at least at 1.5 m (0.5 m + 1.0 m) above the soil surface. In this case, the site should provide a fetch of about 150 m. In regions with winds from multiple directions, it would be ideal to find a site of at least 300 × 300 m, so that the tower can be placed in the centre and can collect data from all directions, minimizing data loss. In regions with a single or only a few prevailing wind directions, the tower can be positioned on the downwind edge of the measured area, reducing the minimum size requirement to 150 m × 150 m.

2.3.4 Instrumentation

An eddy covariance system is essentially a fast response measurement apparatus consisting of sonic anemometer and trace gas analyser. However, a suit of slow-response research-grade sensors also form a part of flux station for supporting observations. The entire setup requires a robust data logger that can synchronize the measurements done by the variety of fast and slow-response analog or digital sensors. Some data loggers have in-built programmes that can process the high-frequency raw data and provide real-time flux estimates at hourly or sub-hourly time scales. However, it is always advisable to script your own programme to process the high-frequency data and impose site-specific criteria for data correction and screening. For a more comprehensive study on GHG exchanges over agro-ecosystems including the understanding of regulatory processes, observations on some additional factors are advised. Table 2.1 presents an exhaustive list of such sensors/equipments.

Table 2.1 Eddy covariance system components and related sensors/equipments for a comprehensive study on GHG exchanges over agro-ecosystems

Sensors/parameters	Models
1. *Core components*	
3-D sonic anemometer (three-dimensional wind speed)	CSAT-3 (Campbell Scientific); R3 and HS series anemometers (gill instruments); model 81,000 ultrasonic anemometer (young); uSonic series (Metek)
Krypton hygrometer (density of H_2O)	KH20 (Campbell Scientific)
CO_2-H_2O gas analyser (density of CO_2 and H_2O)	Open-path type: IRGASON, EC-150 (Campbell Scientific) Open-path type: LI-7500A (LI-COR Biosciences) Enclosed type: LI-7200 (LI-COR Biosciences) Closed-path type: LI-7000 (LI-COR Biosciences)
CH_4 analyser (density of CH_4)	Open-path type: LI-7700 (LI-COR Biosciences)
Fine-wire thermocouple (absolute temperature)	FW05 (Campbell Scientific)
Data logger (storage and processing of raw data and or on-line flux computations)	CR-3000, CR-1000 (Campbell Scientific)
2. *Auxiliary/meteorological sensors*	
Soil CO_2 flux system along with atmospheric CO_2 profiling kits (soil respiration and canopy storage of gases)	LI-8100A (LI-COR Biosciences)
Air temperature and humidity sensors	HMP155A (Vaisala)
Anemometer and wind vane (wind speed and direction)	*Mechanical-type anemometer*: Propeller- or cup-type anemometers (Gill) *Combined mechanical type*: Wind sentry and wind monitor series (Young) *Combined ultrasonic type:* 86000 series (Young)
Barometer (atmospheric pressure)	Digital: 7150 series (All Weather Inc); DBT-100 and DBT-100 T (CNMC)
Rain gauge(rainfall)	*Tipping bucket type* TE25 (Campbell Scientific); 5600-0425 series (Sutron Corp.)
Net radiometer (net radiation and/or its various components)	CNR4 (Kipp & Zonen), NR01 (Hukseflux)
Soil heat flux plates (upward or downward fluxes of heat in soil) heat	Non-calibrating type: HFP01 (Hukseflux) Self-calibrating type: HFP01SC (Hukseflux)

Table 2.2 Sensors for crop biophysical and soil property measurements

Sensors/parameters	Models
Leaf area meter (leaf area index)	LAI-2200 plant canopy analyser (LI-COR Biosciences); ACCUPAR LP-80 (Decagon Devices)
Quantum sensor (incoming and intercepted photosynthetically active radiation, PAR by the vegetation canopy)	Point quantum sensor: SQ-224 (Apogee Instruments) Line quantum sensor: LI-190R, LI-191R, LI-191SA (LI-COR) SQ-311 (Apogee Instruments)
Photosynthesis system (leaf photosynthesis)	LI-6400XT (LI-COR); GFS-3000 (Walz)
Hyperspectral spectroradiometer (canopy growth, vigour and stress)	FieldSpec 4 (ASD Inc.), PSR-1100F (Spectral Evolution)
Infrared thermometer (canopy stress)	Agri-Therm III series (6110 L/6210 L) (Everest Interscience Inc)
Soil temperature probe	TCAV (Campbell Scientific)
Soil moisture probe	CS616, CS 625 (Campbell Scientific)

- The models mentioned above are only examples and not endorsement to any manufacturer. (Tables 2.1 and 2.2).

Selecting good equipment and its proper maintenance is necessary as it would reduce the occurrence of noise in the data. As far as possible, low power requiring setup should be preferred so that carbon emission by the instrument itself remains low and there is little or no impact on the fluxes of the crop surface of interest. During the flux station establishment, the tower which supports the sensors should be made steady with concrete basement support of appropriate strength and if required by fixing guy wires. The sonic anemometer should be installed perfectly horizontal because if unlevelled it will affect all fluxes by contaminating the vertical wind speed with a horizontal component. The shape of the sonic anemometer should be aerodynamic so as to minimize wind distortion. The EC system should have fast enough response time to catch all the rapid changes that result from the eddy transport. Sensor integration ideally should be such that the sample measurements by sonic anemometer and gas analyser represent the same volume of air and that covariance is computed for parameters that were measured at the same point of time. However, because of physical limitations of most available models, such ideal arrangement is difficult to achieve, and this introduces some error in flux measurement. In the absence of any choice, the mid-axis horizontal separation distance between the sonic anemometer and gas analyser should be kept to a minimum, preferably not exceeding 10–15 cm. Recently, a physically combined model (IRGASON, Campbell Scientific), i.e. no separation distance between the two aforesaid sensors, is available in the market, but information regarding its field performance has not been widely reported so far. For open-path system, the sensor head of the gas analyser can be slightly tilted to minimize the amount of precipitation accumulating on the windows.

GHG measurements using the eddy covariance technique require significantly higher capital investment than that of chamber method or other micrometeorological methods. High costs are due to sophisticated nature of the sensors for detecting fast changes, the need for a suit of auxiliary instruments (e.g. weather station), and supporting hardwares (tripods or mast). Even with minimum recommended set of auxiliary sensors, initial investment in instrumentation for measurement of CO_2 and energy fluxes only is around Rs. 40–50 lakhs. To add other sensors such as for CH_4 (open-path sensors are available) and N_2O (requiring laser spectroscopy instruments) would require additional investments as high as Rs. 20–30 lakhs per gas. If the focus of the study is other than open-path measurement of $CO_2/H_2O/CH_4$, then external energy supply to the system is required, thus adding some more constraints and raising the cost. More information on processing tools for GHG flux calculation and expertise support for designing, establishing and running micrometeorological instruments could be availed from multisite, multi-year observation networks such as AmeriFlux (http://public.ornl.gov/ameriflux), AsiaFlux (http://www.asiaflux.net); National Ecological Observatory Network (NEON), USA, (http://neoninc.org/); and Integrated Carbon Observation Network (ICOS), Europe, (http://www.icos-infrastructure.eu) among others.

2.4 Measurement Issues: Data Screening, Corrections and Gap Filling

It is often seen that a site chosen for GHG measurement does not represent the ideal condition which is required for application of eddy covariance methodology. For example, the topography may be undulating or having steep slope, and there could be obstruction along the wind path. Furthermore, during stable atmosphere and calm conditions with very low wind velocity, either turbulence does not fully develop or the footprint may become so large that it exceeds the target area of measurement. There could be other issues which produce errors such as intense rainfall events, wrong instrument setup, sensor failure or aberrations, and certainly there is technology limitation which does not guarantee the theoretical perfection during measurement. During computation of mean fluxes from high-throughput raw data, appropriate correction measures need to be applied. Further, certain quality criteria need to be used to flag suspected bad flux data and screen them out. The above steps eventually lead to some missing values. Data gaps in the flux time series should be filled in using appropriate techniques for a valid inference.

2.4.1 Errors: Causes and Correction Measures

Even though modern flux programmes will automatically correct most of the errors as part of the standard flux processing sequence, it is still extremely important to minimize or eliminate the majority of these errors during the experiment setup and only then to correct the remaining errors during data processing. Another important fact is that most of the principles that are used for flux corrections and commonly reported in literature have been developed and tested for traditional settings, over reasonably horizontal and uniform terrains, with negligible air density fluctuations and negligible flow convergence and divergence and with prevailing turbulent flux transport. In recent times, several research groups have started working under conditions that violate the basic assumptions such as complex terrains, hills, flow obstructions and limited footprint in order to come out with methodologies that ensure reliable measurements. There are at least 25 stations across the globe under FLUXNET and other networks that operate in complex mountainous terrains (Burba 2013).

Various types of errors that occur during measurement by the EC system and affect the final fluxes are discussed below:

- *Spikes and noise*: These are abrupt datapoints occurring in a time series that cannot be explained by the underlying ecosystem processes that govern its neighbouring datapoints. These are most common features in any flux dataset and mostly arise due to electrical fault of the sensors. Based on some reasonable statistical criteria such as standard deviation thresholds, these errors can be eliminated.
- *Frequency response error*: If placed very close to the canopy (say inside the roughness layer), the eddy covariance sensors' response time may fall short to resolve smaller eddies which are prevalent in that zone. This kind of error affects all type of fluxes and is more severe in long-tube closed-path system than open-path system. By choosing sensors with faster response time and placing those away from the roughness layer would minimize such errors. The remaining errors can be removed using flux processing software.
- *Sensor responses mismatch*: Errors due to unadjusted time delay of sensors can affect all fluxes but are most severe in closed-path systems. Sticky gases such as water vapour (H_2O) and NH_3 are more highly affected than nonsticky gases. In general, time delay can be minimized through time synchronization, i.e. using instruments with matching clocks, by minimizing the separation distance between the intake/path of the gas analyser and the sonic anemometer. For closed-path system, when possible shorter tubes can be used. The delay between two time series can also be computed from the known flow rate and tube diameter of a closed-path system. In open-path system too, time delay error can be virtually eliminated during data processing by adjusting the delay. This is implemented by shifting the two time series in such a way that the covariance between them is maximized.
- *Density fluctuations error*: It mostly affects gas and water fluxes and when instruments output fast density. Size and direction of the related errors vary greatly. For example, the error could be 300% of the small magnitude fluxes in winter or only a few percent in summer. These errors can be eliminated by choosing instruments that output fast dry mole fraction or can be corrected

using Webb-Pearman-Leuning (WPL) density terms (Webb et al. 1980) using software/computer programmes.
- *Band-broadening errors*: These affect gas fluxes measured by the NDIR technique and depend greatly on the instrument used. The error can be fixed by applying corrections in the instrument's software or described by the instrument manufacturer. Oxygen in the gas analyser path affects krypton hygrometer readings, and the error is fixed with an oxygen correction.
- *Coordinate rotation*: For non-flat terrain or rolling topography, one additional correction, viz. coordinate rotation, is applied to streamline the data (Zhilin et al. 2005).

2.4.2 Missing Data and Gap-Filling Techniques

Occurrence of gaps, i.e. missing values in eddy covariance flux data series, is a common problem. Typically, the quantum of gaps in annual datasets, across sites, exceeds 20%, and cases where the missing frequency has even exceeded 50% are not uncommon (Falge et al. 2001; Moffat et al. 2007). Data gaps do not occur randomly in the half-hourly dataset. Apart from instrument failure, majority of the gaps occur mostly during night time owing to the stable condition of the atmospheric. Gap filling of the flux data is essential especially when long-term experiments are to be evaluated.

So far, no single method has been prescribed in literature as the standard that suits all situations, and new methods or modifications of the existing techniques are continuously being evolved by the research community. The appropriateness of a method depends on the unique conditions of the flux measurement site and end use of the flux data. For example, one who is interested in determining seasonal or annual carbon budgets or comparison of fluxes with biometric measurements may choose non-linear regression methods. On the other hand, those preparing complete half-hourly datasets for process-based SVAT model validation may choose artificial neural network (ANN) techniques. Also, while some methods such as non-linear regression methods and SVAT simulation models essentially require the ancillary meteorological data during the missing flux observations, others can do away with such requirement. The latter group includes methods such as mean diurnal variation (MDV) and ANN. Some of the gap-filling approaches are discussed below.

2.4.2.1 Mean Diurnal Variation

This is a simple interpolation technique. In this method, a missing observation is replaced by the mean for that time period (half-hour) of few adjacent days. Bin-averages of half-hourly fluxes for the diurnal time period are calculated by considering a time window around each gap. Depending on the environmental condition and the parameter of interest, the length of the window may be varied and sizes between 4 and 15 days have been reported in literature. Too short a time window such as <4 days may not be enough as spectral peaks of fluxes are reported to occur at 3–4 days (Baldocchi et al. 2000). On the other hand, a large window should not be considered while filling gaps in carbon fluxes as it is non-linearly dependent on environmental variables (Falge et al. 2001).

2.4.2.2 Multiple Regression

In this method, a multiple regression relationship is established between a flux quantity (which is to be gap filled) and its main controlling variables. A regression relationship for each missing value is calculated using the data from the adjacent few days, before and after the missing data. If, in the resulting equation, independent variables explain sufficient variability in the fluxes of interest, then missing data are gap filled. Alavi et al. (2006) used this technique for latent heat flux (LE) using net available energy (net radiation minus ground heat flux) and vapour pressure deficit as the main controlling factors. Only those regression equations were used in which R^2 exceeded the value 0.5, and when such criteria did not meet, the gaps were not filled. For short and long gaps (missing data for more than 5 days), they used windows of ±10 days and ± 20 days period, respectively.

2.4.2.3 Semiempirical Methods

Semiempirical methods retain the response of the parameter, whose values are to be gap-filled, to temperature and flux density of photosynthetically active radiation as observed in the data. These methods fall mainly in two groups, viz. look-up table approach and non-linear regression approach.

Look-Up Table (LUT) In this approach tables are created for a given site. The NEE data are binned by variables such as light and temperature presenting similar meteorological conditions, so that a missing NEE value with similar meteorological conditions can be "looked up" from the table. Look-up table methods allow for variable response, i.e. the shape of a light response can vary between linear and rectangular hyperbolic, based on the data analysed.

In standard LUTs fixed periods of a year are considered with corresponding fixed intervals for the variables (Falge et al. 2001). An improvement to the standard fixed LUT is a moving LUT technique, also called marginal distribution sampling (MDS). Here, similar meteorological conditions (of a fixed margin) are sampled in the temporal vicinity of the gap to be filled (Reichstein et al. 2005).

Another type is the semi-parametric model technique (SPM) which can be seen as three-dimensional, non-linear look-up table sorted with environmental variables of interest (e.g. solar radiation and soil moisture) and time. SPM represents the continuity of the response of NEE to the environmental variables (Moffat et al. 2007).

Non-linear Regressions (NLRs) The non-linear regressions are based on parameterized non-linear equations between the NEE flux and environmental variables. Each technique (Falge et al. 2001; Hollinger et al. 2004; Desai et al. 2005; Richardson et al. 2006; Noormets et al. 2007) uses one equation for the ecosystem respiration (ER) based on temperature and one equation for the light response of the ecosystem, which is the gross primary production (GPP). NEE is estimated by subtracting ER from GPP with GPP equal to zero at night due to the absence of photosynthesis. The parameterized equations are fit to the observed data and then used to fill missing NEE values.

The modelled relationships of respiration vary from technique to technique. The most common are semiempirical equations with an exponential or logistic dependence on temperature. The response of GPP to the photosynthetic photon flux density PPFD is modelled using rectangular hyperbolic functions. The entire year is divided into various time windows as per the variations over the year and the regression parameters of the equations are kept constant within each window but varied outside it (Falge et al. 2001).

2.4.2.4 Multiple Imputation (MI)

In this technique, the missing values of a dataset are simulated multiple number of times using the Markov chain Monte Carlo algorithm (Schafer and Olsen 1998; Hui et al. 2004). The variation among the multiple imputations reflects the amount of uncertainty with which the missing data can be predicted from the observed ones. Each set of imputed datapoints (observed and simulated values) is analysed using normal statistical metrics. The results are finally pooled and averaged to provide the missing NEE data. Past studies (Schafer 1997) have shown that the violation of the normality assumption of values used in the analysis does not take away MI’s robustness when the amount of missing values is not large. Three to five imputations are enough to estimate the missing data if the rate of missing data is not very high (Rubin 1987; Schafer and Olsen 1998).

2.4.2.5 Artificial Neural Networks (ANNs)

The concept and structure of artificial neural networks (ANNs) is in close analogy to that of neural networks in biological systems. An ANN consists of some purely empirical non-linear regression models (also called as nodes) that are interconnected together by regression parameters (also called as weights). The network is trained by presenting it with sets of input data such as meteorological variables and associated output data, for example, fluxes. Classical back-propagation algorithms are used in the ANN techniques. The training is performed by propagating the input data through the nodes via the weighted connections and then back-propagating the error and adjusting the weights so that the network output optimally approximates the fluxes. Examples of gap filling of missing eddy covariance flux using various ANN techniques include the works of Papale and Valentini (2003), Braswell et al. (2005) and Moffat et al. (2007).

2.4.2.6 Process-Based Models

It may happen some times that the data, available to construct the mean diurnal variation or regression equations, is biased towards a particular condition and hence the resulting fit or mean diurnal variation may not represent the conditions in the gap. Process-oriented ecosystem gas exchange models, parameterized from independent datasets, are the best option to simulate missing data in such case. Also, for sites with many and large data gaps, process models may prove to be better than other gap-filling methods. However, these are more input intensive and complex to develop as specific computer programming is required. Example includes biosphere energy-transfer hydrology (BETHY) model (Knorr and Kattge, 2005).

2.4.3 Other Approaches

Application of recursive parameter estimation algorithms based on Kalman filtering can be found in literature. Researchers have used various forms of filters such as ensemble Kalman filter or dual unscented Kalman filter for gap filling of GHG fluxes such as CO_2 (Jarvis et al. 2004; Williams et al. 2005; Moffat et al. 2007) and various components of energy balance including water vapour flux (Boni et al. 2001; Alavi et al. 2006). For gap filling of latent heat, i.e. water vapour flux data, standard evapotranspiration equations such as Penman-Monteith (Allen et al. 1998), Priestley-Taylor (Alavi et al. 2006), etc. can be used.

2.5 Flux Validation

The most common approach for validating the fluxes measured with the eddy covariance method is to construct an energy budget for the study site. The principle behind this concept is the energy balance closure, i.e. the net energy which is available to the system is spent in maintaining the key ecophysiological processes, viz. sensible heat transfer between surface and atmosphere (H) and latent heat flow (LE) due to evapotranspiration. Net available energy can be obtained by deducting ground heat flux (G) and heat stored in the system (S) from the net radiation (Rn). If the closure is good, i.e. if there is a good agreement between the net energy and turbulent fluxes of sensible and latent heat, then by analogy we can infer that turbulent fluxes of trace gases/GHGs such as CO_2, CH_4 or N_2O measured by the EC system are most likely to be corrected as well. However, it should be kept in mind that there is inherent difference in the method of measurements of available energy and turbulent fluxes. One can also argue that a good measurement of, say, latent heat flux does not necessarily mean a good measurement of the trace gas, because transfer processes and sources/sinks of water and other gases, especially reactive VOCs (volatile organic compounds), may significantly differ compared to water vapour. Hence, it can be said that a good (closed) energy budget will not necessarily indicate good measurements of the trace gas flux, while a “non-closing” energy budget will almost certainly indicate a problem in the measured flux.

At least four different indicators (Li et al. 2005; Wilson et al. 2002) have been cited in literature to infer on the degree of closure of energy balance. For example, linear regression coefficients (slope and intercept) of the relationship between the half-hourly turbulent fluxes (dependent variable) against the net available energy (independent variable) derived from the ordinary least squares or reduced major axis techniques can be taken as indicators. When the slope is one and intercept zero, that condition represents ideal closure. In general, a slope of 0.7 or above is good enough indication of closure under practical field situations.

The third indicator is energy balance ratio (EBR), which is a ratio of turbulent heat flux to net available energy.

$$\mathrm{EBR} = \sum(\mathrm{LE} + H) / \sum(\mathrm{Rn} - G - S)$$

The closure can also be inferred from frequency distribution of relative errors of energy balance (δ). It is a ratio of the residual in the energy imbalance to available energy.

$$\delta = [(\mathrm{Rn} - G - S) - (\mathrm{LE} + H)]/(\mathrm{Rn} - G - S)$$

Here, $\delta = 0$ stands to refer a perfect closure. Positive values of δ would mean underestimation of turbulent fluxes, and negative ones would mean that turbulent energy fluxes are higher than the net available energy. The latter situation could arise due to edge effect or advection.

A comprehensive evaluation of energy balance closure by Wilson et al. (2002) which included 22 FLUXNET sites and 50 site-years showed that energy imbalance is a common phenomenon across vegetation types in climates ranging from Mediterranean to temperate and arctic. The average magnitude of such imbalance was around 20%, and in general the imbalance was higher during the night- than during the daytime conditions. They also suggested a link between the energy imbalance and CO_2 fluxes. For a given value of photosynthetically active radiation, the magnitude of CO_2 uptake was found to be less when the energy imbalance was greater. Similarly, respiration was found to be significantly less when the energy imbalance was greater. In general, the problem of energy balance closure is less severe in agro-ecosystems than that of tall forests owing to smaller surfaces roughness in the former compared to the latter.

2.6 GHG Fluxes from Agro-Ecosystems

Agricultural activities account for about 10–15% of the global emission of greenhouse gases (IPCC 2007). It releases a significant amount of CO_2, CH_4 and N_2O into the atmosphere. The GHG budgets in agricultural fields are affected by structure and dynamics of anaerobic and aerobic conditions in the soil, nutrient and other management practices, growth stage, environmental conditions or stresses. A wide range of values of fluxes and often conflicting inferences about the source or sink nature of some agro-ecosystems can be found in literature. The reasons could be the factors as stated above and also because no single methodology is used for measurement, data processing and quality control. Furthermore, before comparing experiments or to draw valid inferences on agro-ecosystems, care should be taken to note differences in terms of monitoring period, crop rotations, intermittent fallow periods, measurement units, externally added inputs, harvest removal, left over residues etc.

2.6.1 Carbon Dioxide (CO_2)

Measurement of carbon dioxide fluxes in relation to plant physiological processes such as photosynthesis and respiration and dynamics of environment are vital for understanding the agro-ecosystems behaviour and prediction of climate change. An eddy covariance system measures the rate of CO_2 exchange at ecosystem scale, also termed as CO_2 flux or the net ecosystem exchange (NEE) rate, which takes into account both the photosynthetic gain and respiratory losses of carbon. Whether an agro-ecosystem act as a source or a sink of CO_2 could be assessed based on the seasonal NEE values and ancillary data on biomass removal, leaf shedding and extraneous inputs such as organic manures and crop residues.

The flux at any time during the growing season is directly or indirectly governed by various biophysical and environmental factors such as crop growth stage, global radiation, photosynthetically active radiation (PAR), net radiation, ambient temperature, soil moisture, soil temperature, vapour pressure and rainfall (Anthony et al. 2004; Suyker et al. 2004; Posse et al. 2010; Hernandez-Ramirez et al. 2011; Bhattacharyya et al. 2013; Guo et al. 2013). In the beginning and towards the end of the crop season, agro-ecosystems behave as net source of CO_2 as the respiratory losses exceed the photosynthetic carbon fixation due to low plant cover and senescence of the green tissues, respectively. If the diurnal cycle is considered, an ecosystem invariably becomes a source of CO_2 during nighttime, whereas during daytime period, it can be either a source or a sink depending on meteorological conditions particularly solar radiation. With fully developed canopies, available light becomes the main driver of daytime CO_2 uptake. Suyker et al. (2004) observed such relation between NEE and incident light in maize. Similarly, Hernandez-Ramirez et al. (2011) observed that in corn and soybean under non-limiting soil water availability conditions, seasonal variations of CO_2 fluxes were mostly controlled by ambient temperature and available light.

For a good number of crops such as soybean, winter wheat, rapeseed and sugar beet, daily average net assimilation fluxes between -9 and $-$ 13 g C m^{-2} have been reported in literature (Baldocchi 2003; Soegaard et al. 2003; Anthoni et al. 2004; Hollinger et al. 2005; Moureaux et al. 2008; Béziat et al. 2009). Bhattacharyya et al. (2013) compared fluxes from rice paddy under both flooded and aerobic field conditions and from studies conducted across Asia (countries included were India, Bangladesh, Philippines, Taiwan and Japan). They reported NEE values ranging between -300 gC m^{-2} and $-$ 85 gC m^{-2} per growing season which when converted to daily scale would mean a maximum uptake rate of about -2.5 gC m^{-2} d^{-1}. Saha et al. (2014, 2016) reported even lower values of NEE, which was -1.6 gC $m^{-2}d^{-1}$ as mean of the season and 558 gC $m^{-2}d^{-1}$ for the green manuring crop *Sesbania aculeata* and wheat crop, respectively, grown under semiarid rainfed condition with severe soil depth limitation. Despite large annual exchanges of CO_2 between agro-ecosystems and the atmosphere, net flux is approximately balanced with soil contributing less than 1% of global anthropogenic CO_2 emissions and estimates for agricultural lands hovering around 0.05 Gt of net CO_2 emission per annum (US-EPA 2007).

2.6.2 Methane (CH_4)

Soil condition and organic wastes strongly influence atmospheric CH_4 concentrations. CH_4 emission increases under continuous flooding condition. It is estimated that wetland and paddy soils represent approximately one third of all sources for atmospheric CH_4 (Fowler et al. 2009). On the other hand, natural and seminatural ecosystems and to some extent non-paddy agro-ecosystems, due to aerobic soil conditions, act as sinks and remove approximately 20–45 TG year^{-1} of CH_4 (approximately 6–8% of all sinks) from the atmosphere (Dutaur and Verchot 2007; Fowler et al. 2009).

2.6.3 Nitrous Oxide (N_2O)

The global estimate of nitrous oxide (N_2O) flux emitted from agricultural land is 2.3–3.7 Tg N year^{-1} (Bouwman 1990) which is about one-fourth of the global N_2O emission. Nitrous oxide (N_2O) is emitted from the nitrogen fertilizers, legume cropping, animal waste and biomass burning. The gas is generated by the microbial transformation of N in soils and manures, and is often enhanced where available N exceeds plant requirements, especially under wet conditions (Oenema et al. 2005). Primarily it is emitted in pulses after fertilization and strong rainfall events. Rice paddies act as major sources of N_2O and nitrogenous fertilizers such as urea appears to be the single most important factor that controls its emission from flooded rice fields.

Chao (1999) estimated N_2O emission of around 0.67 Mg N year^{-1} from the paddy fields of Taiwan. Chen et al. (1997) estimated 39–164 mg m^{-2} h^{-1} of N_2O-N emission for the Chinese rice fields. For crops such as soybean and maize, Chen et al. (1997) reported emissions of the order of 3.1–7.1 kg N_2O ha^{-1}. In India, agriculture-related activities account for around 90% of the total N_2O emissions (Garg et al. 2001). Bhatia et al. (2004) reported annual N_2O emission of about 80 Gg from Indian agricultural fields. For irrigated and upland paddy fields of India, annual N_2O emissions of about 4–210 and 2–10 Gg, respectively, were reported by Sharma et al. (1995). The total N_2O emission from Indian rice and wheat fields was put at 199–279 Gg year^{-1} by Parashar et al. (1998), whereas Aulakh et al. (2001) reported that the irrigated rice-wheat system could emit about 15 kg N_2O-N ha^{-1} year^{-1}.

2.7 Measurement of GHG Fluxes in Some Crop Ecosystems of Indian Peninsula: Case Study

A flux monitoring tower with an open-path eddy covariance system (EC-150 and CSAT3 combination, Campbell Scientific) was installed in the research farm of ICAR-National Institute of Abiotic Stress Management, Baramati, Pune, India in August 2013.The physical separation between the two aforesaid sensors was only 2 inches (mid-axis separation distance) which minimized error in flux measurement.

Fig. 2.3 Eddy covariance-based GHG measurement in *dhaincha* (*Sesbania* spp.), wheat and soybean ecosystems in the years 2013 and 2014

A fast-response fine-wire thermocouple (FW05, Campbell Scientific) was attached with the sonic head of the EC system for absolute temperature measurement. In addition to the eddy covariance component, the tower was also equipped with a suit of slow-response research-grade sensors that were needed for flux validation through energy balance closure principle and recording micrometeorological conditions near the crop surface. These include one 4-component net radiometer (NR01, Hukseflux), two soil heat flux sensors (HFP01, Hukseflux), two soil moisture sensors (CS616, Campbell Scientific), two soil temperature sensors (TCAV, Campbell Scientific) and one sensor for ambient temperature (HMP155A, Campbell Scientific) measurement.

Seasonal NEE rates were monitored in three different crops, viz. dhaincha (*Sesbania aculeata*), wheat and soybean (Fig. 2.3). During each growing season, measurement protocol was standardized as per site condition so that minimum data is lost during the post-processing screening steps. This was done by suitably orienting the eddy covariance sensors keeping in view the mean seasonal wind rose pattern (wind direction and speed) and availability of fetch in different directions and also by adjusting the sensor height as per crop.

Hence, while during *dhaincha*-growing season the EC sensor faced west with a maximum height of 3 m from the ground, in wheat and soybean seasons, the heights varied between 1.8 and 2 m and the EC sensors had a 300° azimuth orientation. In all seasons, about 2 ha area around the flux tower was maintained under a single crop ecosystem. As all the three crops, considered for the study, were of short height (< 2 m), gas storage within the plant canopy was considered negligible, and hence CO_2 profiling in the crop microclimate was not undertaken. The EC system measured all the parameters diurnally (24 hours of the day) throughout the season. The fast data was sampled at 10 Hz frequency which was subsequently processed, including density correction using Webb et al. (1980) method, by the CR-3000 data logger programme, and produced measures of turbulent fluxes (CO_2, sensible heat and latent heat) in real time on a half-hourly time scale. Data on ground heat flux, soil moisture and temperature and meteorological conditions were also generated and stored in the data logger on half-hourly basis. Time series flux data (half-hourly) of each season was put to stringent screening process. Thresholds for various quality control criteria were selected after trial and error and were applied uniformly to all the three crops. Suspicious flux data were filtered out based on data logger diagnostic warnings, standard deviation criteria (5 SD) for noise and spikes, frictional velocity criteria (0.1 ms^{-1}) for low wind/stable atmospheric conditions, any rain events, low signal strengths (< 0.70) of turbulent data acquisition and wind flow from a sector that was at the back of eddy covariance sensors (tower shadow effect). The screened dataset were then divided into day (0630 AM to 0600 PM) and night (0630 PM to 0600 AM of next calendar date) halves keeping in view the local sunrise and sunset timings. A 5-day moving average interpolation method was used to fill the gaps in the quality controlled datasets and compute seasonal rates of daytime and nighttime fluxes. A summary of processing attributes and seasonal CO_2 flux characteristics is presented in Table 2.3. As it is observed that a considerable percentage of flux data are missed out during the screening process, different gap-filling strategies may be applied to determine the uncertainty involved in such measurements. It will help towards a more informed interpretation in terms of source/sink potential of different crop ecosystems in respective growing seasons as well as intercomparison among them.

- Observation in *dhaincha* and wheat excludes observations for some part in the beginning of the season.

Table 2.3 Seasonal statistics of net ecosystem exchange (NEE) of CO_2 from various agricultural crops at NIASM, Baramati

Dataset attributes and flux characteristics	*Dhaincha*	Wheat	Soybean
Half-hourly NEE datapoints in the time series	n = 4296	n = 3882	n = 4205
Suspicious NEE values (major sources)			
Data logger diagnostics warning	6.8%	2.4%	7.6%
Low frictional velocity of wind (0.1 ms^{-1})	18.4%	46.8%	29.0%
Tower shadowed fluxes	30.8%	25.2%	6.5%
Original NEE datapoints retained	n = 2867 (66.7%)	n = 1206 (31.1%)	n = 2393 (57%)
Flux observation period	9-Aug 13 to 29-Oct13	18-Dec13 to 9-Mar14	25-Jul 14 to 20-Oct14
Seasonal CO_2 flux statistics of NEE ($\mu mol\ m^{-2}\ s^{-1}$)			
Daytime rate	−7.6	−7.1	−5.2
Nighttime rate	4.6	3.1	3.2
Estimated net uptake rate	−1.5	−2.0	−1.0

2.8 Conclusions

In an agro-ecosystem the crop undergoes substantial changes in terms of vegetation cover (LAI) and canopy architecture in a relatively short period which is also associated with a large corresponding variation of CO_2 and other trace gas fluxes, including a sign reversal for CO_2 during the season. In addition, agro-ecosystems are often smallholding one, thus causing additional variability on account of differential land use and management practices. In case of chamber-based monitoring of GHGs, proper sampling strategy in both space and time would be vital. On the other hand, for micrometeorological eddy covariance method, proper site selection and site-specific data processing protocol assume great importance. When resources are available, a combination of well-designed sampling scheme using chambers and eddy covariance system would be the best for GHG monitoring in agro-ecosystems as it offers for data cross validation and flux partitioning into various components. Nevertheless, eddy covariance method has emerged as the preferred choice of flux research community worldwide. EC measurements using tunable diode laser absorption spectroscopy and quantum cascade laser absorption spectroscopy are nowadays available for improved trace gas (NH_3, N_2O, NO_2, CH_4 and CO_2) analysis.

During implementation of EC-based monitoring, special care must be taken in sensor orientation and height, keeping in mind the prevailing wind, surface roughness and fetch availability to obtain meaningful data. Sensors' physique, integration and time response should be appropriate to detect small eddy as those are more common over smooth surfaces, such as bare soil or low canopies. However, even with the best sensors and experimental designs, some data losses would be eventual and appropriate correction and gap-filling measures are required based on specific site features. In addition, observation on field activities and environmental conditions must be recorded along with the GHG fluxes for validation and complete budgeting of GHGs using ecosystem models. Data from a network of eddy covariance towers and satellite imageries can be used in modelling framework to upscale and validate GHG emissions from farmland scale to local or regional level which will help predicting changes in earth's climate.

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3

Methane Emission from Wetland Rice Agriculture-Biogeochemistry and Environmental Controls in Projected Changing Environment

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Abstract

Global atmospheric concentration of greenhouse gases (GHGs) has remarkably increased from the periodic spontaneous increase in anthropogenic activities during the past few decades. The anaerobic wetland rice agriculture has considerable contribution in global GHG emission preferably as methane (CH_4). The share is much elegant for developing countries like China and India. It is essentially important to understand the underlying pathways of methane emission from anaerobic rice agriculture, identifying the possible environmental controls on the emission mechanism. We discussed the possible ways for methane emission reduction and emphasized on the associated mitigation options, with large-scale on-farm adaptation of agricultural research generated tested technologies in rice agriculture.

Keywords

Methane emission · Rice · Elevated CO_2 · Elevated air temperature · Elevated ozone

3.1 Introduction

Our present progress towards the hi-tech modern human civilization is often crumbled by the gradual invasion of negative consequences from anthropogenic global climate change (Chatterjee et al. 2013; Pathak et al. 2016). Proliferated urbanization, massive deforestation, rapid industrialization and excessive use of automobiles

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resulted in a significant increase in atmospheric greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone (O_3) emission, at an alarming rate in the post-industrial revolution era (Chatterjee and Saha 2015). After CO_2, CH_4 is the second most important potent greenhouse gas (GHG) in the atmosphere having its global warming potential about 23 times greater than carbon dioxide on a mass balance basis for 100-year time horizon, if indirect effects are taken into account (Towprayoon et al. 2005), thus having substantial effects on the earth's radiative budget. On molecular basis, it is a much more effective greenhouse gas than CO_2. At present, the CH_4 is contributing ~20% of the anthropogenic global warming effect (IPCC 2001). The tropospheric mixing ratio of CH_4 has increased to 1.78 ppm from its pre-industrial concentration of 0.7 ppm with an average increasing rate of 0.5–0.8% year^{-1} (Khalil and Shearer 1993). Together with other atmospheric GHGs, the increased concentration of CH_4 has been predicted to cause an average increase of the global mean surface temperature in the range of 2–4.5 °C by the end of the twenty-first century (IPCC 2007). Ruddiman and Thomson (2001) estimated ~192 ppb increase in atmospheric CH_4 levels due to early anthropogenic inputs which caused 0.21 °C warming (0.16–0.28 °C) between 5000 cal BP and AD 1700.

Methane (CH_4) known as 'marsh gas', a hydrocarbon and the primary component of natural gas, is emitted during the production and transport of coal, natural gas and oil. The average lifetime of CH_4 in the atmosphere is about 10 years. Most atmospheric CH_4 (~90%) is oxidized by UV-active hydroxyl radicals (OH), while 5–10% is removed from the atmosphere by diffusion into aerobic topsoils for further oxidation by soil microorganisms (Prather et al. 1995). Oxic rhizosphere is the important site of CH_4 decomposition in rice fields (Kimura et al. 2004). Around 70–80% of total annual global CH_4 emission is biogenic in origin, viz. livestock and agriculture sector including rice paddies, biomass burning, waste disposal and natural wetlands that will continue to rise in the near future (Khalil and Shearer 1993). Methane is produced strictly under anaerobic environment, viz. wetlands, sediments, paddy fields, sewage and landfills. The total annual source strength of all CH_4 emissions is about 500 Tg, exceeding the total sink by 37 Tg year^{-1}, accounting for 14% of global emissions (lPCC 1996). There are several sources of anthropogenic CH_4 emission that are responsible for this current CH_4 build-up in the atmosphere. In agriculture, cultivation of rice generated a large quantity of CH_4 because of their distinct floodwater regimes that have long been one of the major contributors to the anthropogenic CH_4 emissions (Chatterjee et al. 2018a). Rice is the only major crop grown on flooded soils. Khalil and Rasmussen (1990) estimate the contribution of wetland rice agriculture to the current atmospheric CH_4 burden in the atmosphere was ~230 ppbv during the last century (20–30% of the total increase in atmospheric CH_4). Rice soils may act as a CH_4 sink until it is flooded (Ko and Kang 2000). The CH_4 average source strength of rice fields ranges from 20 to 100 Tg CH_4 year^{-1} (Prather et al. 1995), constituting about 14–40% (~20%) of global CH_4 emissions from all sources (Khalil and Rasmussen 1990; Tang et al. 2014). Rice agriculture may be defined as continuously flooded, intermittently flooded, or dry land. Flooding, or at least saturation with water, is a prerequisite for the anoxic soil conditions needed to produce CH_4 (Bhaduri et al. 2017). Wetland rice agroecologies provide a limited scope for oxygenation and therefore are a major contributor for the increasing atmospheric CH_4 burden. Globally, irrigated rice (51% of global rice area) has the highest CH_4 source strength followed by rained rice (27% of global rice area) and the deep water rice with intense inundation (10% of global rice area), respectively. In India, rice is cultivated as irrigated, rainfed, deep water or upland. Only 15% of the cultivated area is under upland condition, while the majority of rice cultivation is under wetland condition (irrigated, rainfed and deep water rice).

Current research efforts are focused on quantifying the global CH_4 emissions from major rice ecosystems (irrigated rice, rainfed rice and deep water rice), evaluating the control processes on CH_4 fluxes from the waterlogged rice fields and identifying the mitigation options for CH_4 emissions to maintain or enhance rice productivity in the major rice ecosystems around the world. Much of the uncertainty in the current estimates of global CH_4 emissions from rice cultivation is due to the large spatial heterogeneity of soil properties (e.g., texture, SOC content, pH) and varying management practices (Li et al. 2004b). Aerobic soils under upland rice do not encompass flooding; thus it is considered as a negligible source of CH_4 (Wassmann et al. 2000b; Pathak et al. 2003). The controlling internal variable factors include soil characteristics, rice cultivar selection, and soil microbial dynamics. The external controlling factors, viz. soil temperature, meteorological conditions and cultural practices such as water management and fertilizer and organic matter applications, also have the control on CH_4 emission from wetland rice agriculture (Swain et al. 2018a, b; Chatterjee et al. 2018b). The global CH_4 flux is usually calculated by using Eq. 3.1:

$$F = \Sigma\ \theta_R T_R\ A_R \tag{3.1}$$

where θ_R (g m^{-2} day^{-1}) is the measured, seasonally averaged emission rate over any specific region R; A_R (m^2) is the area of the region, presumably with similar characteristics, so that the region R is an accurate representation of flux for the entire area; and T_R is the length of growing season (days $year^{-1}$). The measured flux (θ_R) must represent the area of our interest and growing season. The global extrapolate is A_R and T_R that can be subdivided into similar homogeneous subregions to calculate the CH_4 flux from rice agriculture across a country. However, the limited number recorded field-scale observations for CH_4 emission over limited periods may not necessarily be representative of average emission rates at the global, national and regional levels to which they are frequently extrapolated.

At present, the Asian counties jointly account for the largest cumulative share in global CH_4 emission (89%), followed by African countries (4–5%) for their ever-expanding huge wetland area under rice paddy cultivation (FAOSTAT 2013). China (30.7 million ha) and India (43.4 million ha) account for ~50% of the global rice area and become the largest CH_4 emitters from wetland rice paddies. We considered the FAO database on annual CH_4 emission from rice cultivation that was computed at Tier 1 following the revised 1996 IPCC Guidelines for National GHG Inventories and the IPCC 2000 Good Practice Guidance and Uncertainty Management in

Table 3.1a Trends (Z values) in CH_4 emission from rice agriculture in major continents around the world (1961–2012)

Region	Z values	Decadal increase in CH_4 emission (gigagram/decade)
World	9.032	969.57
Asia	8.918*	772.81
Africa	9.958*	162.18
Americas	5.783*	73.00
Europe	0.942	19.45
Oceania	3.517*	9.11

National GHG Inventories (IPCC 2000), available by country, with global coverage and relative to the period 1961–2012 along with the projections for 2030 and 2050. The relative share in global CH_4 emission is also very high for these two countries, viz. 21.7% (for China) and 18.8% (for India), respectively. As compared to the early 1960s, rice-cultivated area steadily increased worldwide and will continue to increase over the coming decades to meet the future food requirement of the ever-increasing human population (Table 3.1a and 3.1b). While land resources are shrinking, present trends suggest that tomorrow's rice land will be under even more pressure. It is projected that to meet the regular food demand, continual intensification of rice paddy cultivation under submergence is essential with rapid expansion of paddy cultivation in the coming decades (880 million tons by 2025; Lampe 1995). As a consequence, a significant rise in CH_4 fluxes to the atmosphere is expected worldwide from the submerged rice paddy fields that have the potential to further continue the gradual rise in atmospheric CH_4 concentration, considering the current technological progress as a constant one (Bousquet et al. 2006). The projected estimates for CH_4 emission are displayed in Fig. 3.1a and 3.1b.

Mineral soils are small sinks for atmospheric CH_4, whereas most of the peat soils emit CH_4. CH_4 are often generated from the microbial degradation of organic substances in the anaerobic environment with very low redox potential that prevails in flooded rice fields due to prolonged waterlogging, as well as in lake sediments. The net CH_4 emission from flooded rice fields is the balance between CH_4 production and its oxidation in the soil environment. At first, the microbial consortium hydrolyses the complex organic compounds (polysaccharides, proteins and neutral fats) to CO_2, H_2 and acetate. In the second step, CO_2, H_2 and acetate are reduced to CH_4 by methanogens (Thauer et al. 2008). Plant-mediated transport is the primary mode of CH_4 emission through the aerenchyma cells from rice paddies that constitute as much as 90% of CH_4 transported to the atmosphere (Gerard and Chanton 1993). The aerenchymal network often promotes rhizosphere oxygenation to support root respiration and CH_4 oxidation. More than 50% of the generated CH_4 is oxidized during the early stage of the crop growth that may increase up to 90% at maturity (Tang et al. 2014). However, 30–90% of the CH_4 produced in the agricultural soil is oxidized to CO_2 by methanotrophic bacteria under the aerobic surface soil of rice fields where CH_4 reaches by diffusion (Bosse and Frenzel 1997). In this chapter, we

Table 3.1b Trends in CH_4 emission from rice cultivation in the major rice-growing countries around the world (1961–2012)

Country name	Z values	Decadal changes in CH_4 emission (Gg/decade)
Sri Lanka	+6.12*	10.00
Malaysia	+0.63	0.68
Nepal	+8.39*	10.49
South Korea	−4.71*	−11.92
North Korea	+0.39	2.28
Japan	−9.19*	−78.74
Cambodia	+3.81*	59.62
Bangladesh	+6.56*	48.54
Myanmar	+5.76*	83.10
Vietnam	+8.74*	93.14
Philippines	+6.45*	107.76
Thailand	+8.35*	211.09
Indonesia	+9.50*	250.83
India	+7.88*	238.49
China	−3.75*	−350.99
USA	+5.42*	41.33
Nigeria	+9.13*	57.15
Pakistan	+8.71*	37.67
Madagascar	+8.09*	20.79
Egypt	+5.05*	12.24
Brazil	−4.21*	−26.94
Iran	+7.38*	15.02
Italy	+8.03*	11.12
Guinea	+10.22*	17.65
Tanzania	+9.01*	16.42
Australia	+3.63*	9.31

Source: FAOSTAT (2013); *significant at $p < 0.05$ level

will confine and focus our discussion preferably on the available case studies on submerged wetland rice agriculture in the recent past.

3.2 Mechanisms of the Methane Emission from Wetland Rice

The atmospheric concentration of CH_4 increased by 0.5% per annum because of increased anthropogenic activity (Dlugokencky 2001). Flooded rice fields are one of the largest sources of atmospheric CH_4 in global CH_4 budget (IPCC 2001). The acetoclastic pathway predominates in methanogenesis, whereas the serine pathway is the principal metabolic pathway for CH_4 oxidation in lowland rice (Bhattacharyya

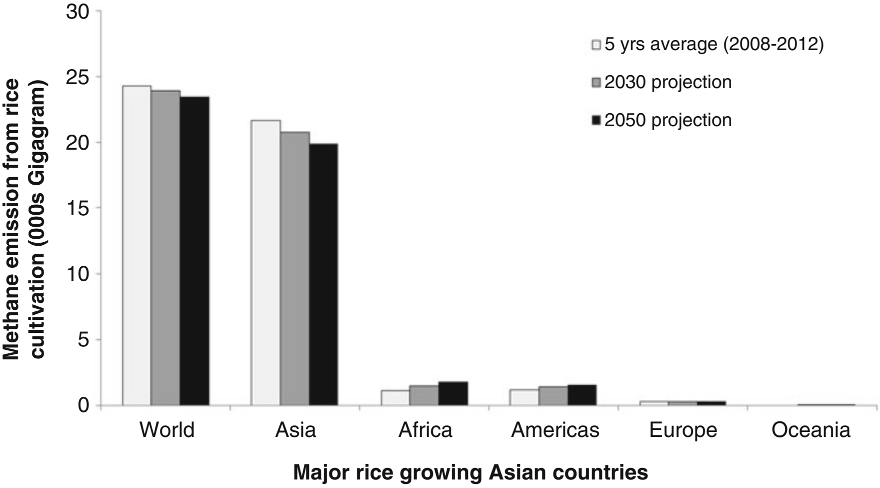

Fig. 3.1a Future projections for regional CH_4 emission from rice agriculture around the world (FAOSTAT 2013)

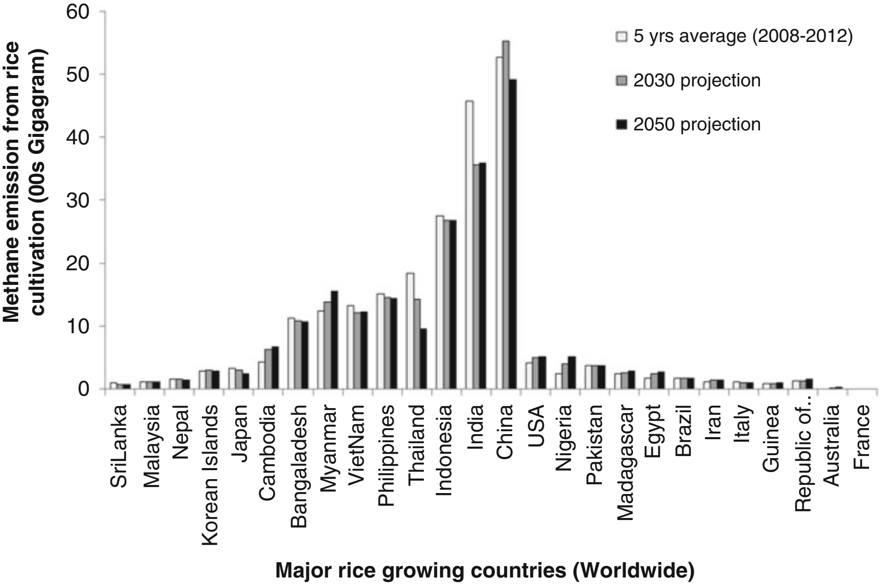

Fig. 3.1b Future projections for methane emission from rice paddy cultivation in major rice-growing countries around the world (FAOSTAT 2013)

et al. 2016). The CH_4 formation in and its subsequent release from rhizosphere environment into the atmosphere are governed by several microbial, physical and physiological mechanisms like the following:

(a) **Methanogenesis-microbiological perspective**

Organic matter mineralizations in flooded wetland rice soils favour the methanogenic bacteria to ferment and produce CH_4 and CO_2.

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4$$

The conversion of complex organic matter to CH_4 requires a microbial consortium composed of several interacting metabolic groups of facultative and strict anaerobic microorganisms (DiMarco et al. 1990): (a) *hydrolytic microflora*, they are either aerobes or facultatively or strictly anaerobes mediating the hydrolysis of large complex biomolecules into glycosides, fatty acids and amino acids monomers; (b) *fermentative microflora*, acidogenesis are the prime activity of this group to various organic acids, alcohols, CO_2 and H_2; and (c) *methanogenic microflora,* this group is involved in methanogenesis from the simple compounds (H_2 + CO_2 and acetate). Methane produced in nature derives about two thirds from the reduction of the methyl group of acetate and one third from the reduction of CO_2 with electrons from H_2 or formate (Ferry 1992). Methanogens proliferate mostly in the strictly anoxic underground environments, contributing to the degradation of organic matter. Methanogens produce CH_4 from various substrates (Table 3.2), but the major substrates for CH_4 production are acetate and H_2+ CO_2.

The major pathways of CH_4 formation are the following (DiMarcoet al. 1990):

(a) *Carbon dioxide to CH_4 reduction:* Chemoautotrophic methanogens reduce CO_2 to CH_4. Carbon dioxide reduction pathway is derived from *Methanobacterium thermoautotrophicum* strains. Studies on these organisms have revealed several novel cofactors involved in the CO_2 reduction pathway and other pathways for methanogenesis.

Table 3.2 List of methanogenic species and its substrate serving as electron donor*

Species name	Substrates that serve as electron donor
Methanobacterium arbophilicum	Hydrogen
M. formicium	Hydrogen or formate
M. ruminantium	Hydrogen or formate
M. mobile	Hydrogen or formate
Methanobacterium thermoautotrophicum	Hydrogen
Methanococcus vannielii	Hydrogen or formate
M. sarcina barkeri	Hydrogen or methanol
M. hungatii	Hydrogen or formate

*Note: Adapted partially from Zeikus (1977)

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$$

(b) *Conversion of formic acid and carbon monoxide to CH_4:* Some microbial strains are also able to use formic acid and carbon monoxide as substrates to produce CH_4.

$$4HCOO^- + 4H^+ \rightarrow CH_4 + 3CO_2 + 2H_2O$$

$$4CO + 2H_2O \rightarrow CH_4 + 3CO_2$$

(c) *Conversion of acetate to CH_4:* The microorganisms involved in this process are *Methanosarcina*, *Methanospirillum* and *Methanothrix*. Acetate is activated to acetyl CoA followed by decarboxylation and methyl transfer in both the genera.

$$CH_3COO^- + H^+ \rightarrow CH_4 + CO_2$$

(b) **Methane transfer from soil to atmosphere-physical and physiological perspective**

Three methods are involved in transfer of CH_4 from soil to atmosphere.

(i) Vascular transport: The CH_4 formed in flooded soils and sediments move towards the surface and are emitted into the atmosphere via aerenchyma cells of vascular plants. Basically these vascular structures have evolved to nourish the supply of O_2 required for root respiration and cell division. However, studies on transport of CH_4 through the aerenchyma of rice by Butterbach-Bahl et al. (1997) demonstrated that the root-shoot transition zone is the main site of resistance to plant-mediated gas exchange between the soil and the atmosphere.

(ii) Ebullition: In this method CH_4 is released into the atmosphere in the form of bubble. In their rice paddy experiment, Bosse and Frenzal (1998) observed that in unplanted and planted microcosms, 85% and 50% of the CH_4 were in the form of gas bubbles, respectively. The range may vary from 4 to 100% across different seasons (Green 2013). Komiya et al. (2015) observed that the daytime CH_4 ebullition in tropical rice paddy took place due to falling atmospheric pressure and increasing soil surface temperature, and at night-time, the drop in atmospheric pressure predominately triggered the CH_4 ebullition. The speed of this process prevents any significant oxidation of CH_4 in the submerged rice paddy environment (Conrad 1989).

(iii) Diffusion: This process is common in submerged paddy, and it is dependent on CH_4 concentration, supply of CH_4 to the water, temperature of the water and wind speed (Sebacher et al. 1983). About 10–40% of total CH_4 diffused to atmosphere get oxidized in rice paddies (Krüger et al. 2002).

3.3 Factors Controlling Methane Emissions from Wetland Rice Agriculture Under Submergence

The average lifetime of CH_4 in the atmosphere is about 10 years. Around 90% of the atmospheric CH_4 are destroyed by the UV-created hydroxyl radicals (OH^-); 5–10% diffuses into aerobic topsoils that get oxidized by different soil microbes (Prather et al. 1995). The CH_4 source strength of rainfed rice is uncertain because of high variability in the strength of different controlling factors of CH_4 emissions from upland rice. The magnitude and variability of CH_4 emission from the lowland submerged rice paddy soils are governed by a complex set of environmental factors linking the physical, chemical and biological characteristics of anaerobic flooded soil environment likewise.

3.3.1 Soil Texture and Soil Structure

Seasonal CH_4 emissions are sensitive to percolation rates of the existing soil profile. High percolation rate (> 20 mm d^{-1}) in coarse-textured sandy loam soils facilitates oxygen entry into the soil environment that promotes CH_4 oxidation. Frequent external irrigation water replenishment in permanently flooded *kharif* rice fields results in low CH_4 emission (16 and 40 kg CH_4 m^{-2} $season^{-1}$; Mitra 1999; Jain et al. 2000). High bulk density (with lower soil/water ratio) retards CH_4 production in wetland rice soils. CH_4 diffusion is seldom limited by water-filled soil pores in the well-drained sandy soils (Carter et al. 2011). Heavy soils entrap more CH_4 for subsequent oxidation, thereby less emission to atmosphere (Neue 1993). The downward movement (leaching) of CH_4 with rapid downward flux of percolating water towards the groundwater reduces the substrate availability to methanogens so as the decrease in net seasonal CH_4 production and emission rates (Inubushi et al. 1992; Yagi et al. 1998).

3.3.2 Soil pH

Methanogens are mostly neutrophilic (pH: 6.5–7.5) but sensitive to soil acidity (Garcia et al. 2000). A few alkaliphilic methanogen isolates from, viz. *Methanosarcina*, *Methanobacterium* and *Methanohalophilus* genera, often dominate with optimum growth pH 8.0–9.0 (Blotevogel et al. 1985). At present, acidophilic methanogenic bacterial strains are rare. The growth of methanotrophs is favoured at more acidic pH ranging from 4.3 to 5.9 (Kamal and Varma 2008).

However, the optimum pH ranges for CH_4 production and consumption vary between the range of soil pH likely 5.5–7.0 and 5.0–6.5, respectively (Dunfield et al. 1993). Flooded rice soils stabilize the soil pH near neutral providing a good scope for methanogenesis to occur.

3.3.3 Soil Redox Potential (Eh)

Anaerobic condition (<-100 mV) promotes methanogenesis in lower range of redox potential (Hou et al. 1998). The critical soil Eh for initiation of CH_4 production varies from -150 to -160 mV. Nevertheless, the redox potential of bulk soil (corrected to pH 7.0) of at least -50 mV is essential for the CH_4 formation. A 50 mV decrease in soil redox level often results in approximately a tenfold increase in CH_4 emission rate for the -150 mV to -250 mV soil Eh range (Masscheleyn et al. 1993). The negative correlation between the CH_4 production and soil Eh is negatively exponential between -230 and -150 mV (Wang et al. 1993). The potential role of depth variation on CH_4 emission from the soil surface is uncertain. The surface layer redox potential is likely to be relevant, since any GHG produced there can easily escape into the atmosphere. For CH_4, the deeper layers might also be relevant as the CH_4 from rooting depth to the atmosphere through rice plants is a well-proved fact.

3.3.4 Soil Chemical Condition

Soils with high ferritic, ferruginous or oxidic mineralogy (strongly acidic pH) are less prone to CH_4 formation. CH_4 production in soil only starts after the complete exhaustion (reduction) of the soil reserve for molecular oxygen, NO_3^-, Fe^{3+}, Mn^{4+} and SO_4^{2-} (all of which maintain a higher potential) (Ponnamperuma 1972). Presence of such chemical ion species in the soil solution prevents the shift of soil environment towards the intense reduced condition and thus reduces the CH_4 production (Achtnich et al. 1995). Increased Fe^{2+} concentration in wetland rice paddies under submergence facilitates CH_4 emissions (Bhattacharyya et al. 2013).

3.3.5 Soil Temperature

The soil temperature of flooded rice soils may vary from 15 °C in northern latitudes to 40 °C in equatorial wetlands. Seasonal and daily soil temperature is likely positively correlated with the increase in daily and cumulative CH_4 formation and emission from wetland rice paddy cultivation. The monthly distributions of global CH_4 emissions were varying between 300 and 1000 mg m^{-2} day^{-1} for 20 to 30 °C temperature range and constant emission of 300 mg m^{-2} day^{-1} for temperatures <20 °C (Aselmann and Crutzen 1990; Cheng et al. 2000). Majority of the methanogenic bacteria are mesophilic (optimum temperature 30–40 °C). In the tropics, the temperature of the reduced puddled layer becomes optimal for methanogenesis. The rate of CH_4 emission doubled with the rise of temperature from 20 to 25 °C that attains maximum at ~37 °C (Holzapfel-Pschorn and Seiler 1986; Sass et al. 1991). Parashar et al. (1993) observed that CH_4 emissions increased for soil temperatures up to 34.5 °C but decreased sharply above 34.5 °C. Low temperatures often limited CH_4 emissions in temperate and subtropical stations such as northern China and northern India (Wassmann et al. 2000a).

3.3.6 Soil Organic Matter

The presence of readily high mineralizable organic matter (as in peat soil), addition of root exudates/degrading roots or incorporation of plant residues and or organic amendments (containing biodegradable organic carbon) into soil provides an array of organic substances for anaerobic degradation via methanogenesis in wetland rice soils. Thus, anaerobic CH_4 production and emission from rice soils are facilitated with subsequent lowering of soil Eh, providing sufficient carbon sources. In tropical lowlands, high temperature throughout the growing seasons also stimulates organic matter degradation and CH_4 emission from rice paddies. The rate of soil organic matter decomposition decreases with soil depth. In deep water rice fields, the anoxic deeper layers of the floodwater may promote methanogenesis during the active crop cycle, if large quantity of organic material is readily available from rice culms, nodal roots and dead aquatic biomass (Whitton and Rother 1988). Earthworms in the topsoils decrease CH_4 formation by promoting aeration but increase CH_4 emissions by enhancing trace gas fluxes.

3.3.7 Soil Salinity

Salinity ($EC > 4\ dSm^{-1}$) reduces the CH_4 emission from flooded wetland rice fields due to more available terminal electron acceptors in situ (Sahrawat 2004).

3.3.8 Rice Cultivar Specificity

Variations in crop phenology and physiological characteristics among different rice cultivars have direct influence on the CH_4 emission from the flooded transplanted rice fields. The number of tillers m^{-2}, root mass, rooting pattern, total biomass and metabolic activity are the emission-related traits that vary among different cultivars of rice crops. The rate of CH_4 emission is higher at mid-tillering than at panicle initiation stage due to more fresh organic matter decompition by amplified methanogenic bacteria population from the greater root activity of the rice, lower rhizospheric CH_4 oxidation rate and more effective transport of internally synthesized methane mediated by rice plants (Bhatia et al. 2011; Suryavanshi et al. 2012). The maximization of photosynthetic carbohydrate assimilation during these specific crop growth stages results in increasing substrate availability for methanogenic bacteria (root exudates and slough off) with more intense reducing conditions that prevailed during the reproductive phase, favouring the formation of more CH_4 (Adhya et al. 1994). The transport capacity of the rice plants is another decisive factor as the plant vascular tissues act as a conduit for CH_4 diffusion from sediments to atmosphere (Tokida et al. 2012). However the total CH_4 emission is positively correlated with the above-ground biomass production in different rice cultivars (Inubushi et al. 2003). Indica cultivars emit more CH_4 than the japonica type (Inubushi et al. 2011; Yun et al. 2012). Furthermore, the CH_4 emissions from the hybrid rice are reported to be lower than that of the traditional rice cultivars, due to the more tillering habit and longer root system, facilitating more CH_4 emission for the traditional rice cultivars (Neue et al. 1996). Semidwarf rice varieties emit less CH_4 (~36%) than the traditional tall rice varieties (Lindau et al. 1995). Satpathy et al. (1998) demonstrated the variability in seasonal CH_4 emission potential may reach fourfold for ten high-yielding rice varieties with similar grain yields tested in India. The seasonal fluctuation of CH_4 emission flux is less for early rice than late rice (Huang et al. 2005). However, the early-maturing rice cultivars with fewer flooding days emit low CH_4 to the atmosphere as compared to late-maturing cultivars (Gutierreza et al. 2014).

3.3.9 Soil Water Regime

Water stagnation in the flooded rice paddy fields hastens anoxic environment either by promoting O_2 depletion for heterotrophic microbial respiration or cutting the external O_2 supply from the outside environment for methanogenesis that enhances net CH_4 emission (Conrad 2007). Flooding in rice fields is reported to increase CH_4 emission varying between 1.17 and 4.76 times than well-drained aerobic condition during the entire crop-growing season (Kang et al. 2002). Continuous submergence in rice paddy cultivation promotes anaerobic environment that stimulates methanogenesis, contributing about 5–19% (60 ± 40 $Tgyr^{-1}$) of the total global anthropogenic CH_4 emission (Bousquet et al. 2006; Khalil and Butenhoff 2008). The depth of water table also has pronounced impact. Sebacher et al. (1986) reported that CH_4 emission rates were linearly related to water depth up to about 10 cm; depths greater than this did not promote CH_4 emission. Draining of flooded rice fields allows free oxygen (due to increased oxygen diffusion rate and air permeability with decrease in soil moisture) to diffuse into soil aggregates and oxidize the existing reduced S, Fe, Mn and N forms. Rice ecosystems under continuous flooding often facilitate the anaerobic environment in irrigated and deep water rice that favours CH_4 emissions from rhizosphere. Irrigated rice was reported to have the highest CH_4 source strength of all rice ecologies in East Asia (~ 97% of the CH_4 emission from rice fields) and South and Southeast Asia (~60% of the CH_4 emission from rice fields). Temporary aeration of flooded rice field reduces CH_4 production. Intermittent flooding or midseason drainage often reduces the CH_4 emission (up to 40%) by increasing O_2 efflux into the soil environment of the paddy fields (Jain et al. 2000;

Johnson-Beebout et al. 2009). Shifting the water management from continuous flooding to midseason drainage was projected to reduce CH_4 fluxes by 4.2–4.7 Tg CH_4-C per year in China (Li et al. 2004b). The emission potentials may also vary based on crop management practices adopted for wetland rice culture. This may favour or lower the actual emission rates in continuously flooded irrigated rice, intermittently flooded irrigated rice, flood-prone rainfed rice, deep water rice, drought-prone rainfed rice and tidal rice (Wassmann et al. 2000a, b; Yan et al. 2009). In rainfed rice, the alternate drying and wetting process is generic that reduces the opportunity for CH_4 production and increases the scope for CH_4 oxidation. System of rice intensification reduces CH_4 emission from submerged paddy fields (Suryavanshi et al. 2012).

3.3.10 Organic Amendment Application

The amount of organic amendments (compost, sludge from biogas pits or crop residues) applied to the submerged rice fields is one of the most important determining factor for CH_4 emission from the soil environment. The release of soluble C compounds from decomposing organic substrates is an important factor that determines the degree of methanogenic activity as well as CH_4 emission from soil environment. Incorporation of organic amendments of endogenous origin, viz. crop residue (rice straw, green manure), or exogenous origin (compost, farmyard manure, etc.) into flooded rice paddy soil increased the CH_4 emission dramatically during the active crop-growing season (Cheng et al. 2000; Johnson-Beebout et al. 2009; Thangarajan et al. 2013). Field application of well-decomposed and comparatively stabilized organic amendments often decreases CH_4 emission by 20% during rice paddy cultivation as compared to fresh manure application (Pramanik and Kim 2014). The in situ combustion of paddy straws enhanced CH_4 emission from rice paddy fields (130%) as the ashes contain much organic carbon for utilization by methanogens that promotes CH_4 emission (Ma et al. 2008; Xie et al. 2012).

3.3.11 Fertilizer N Application

Application of different mineral N fertilizers, especially in combination with FYM, enhances the fraction of bioavailable organic C pools that promotes CH_4 production from the enhanced methanogenic microbial population by the utilization of readily biologically active organic C in flooded rice soils (Fang et al. 2012). Dan et al. (2001) reported the negligible impact of late-season urea fertilization on CH_4 oxidation to the net CH_4 flux from the submerged rice paddy. Under greater N availability in the soil environment (concentration of NH_3: CH_4 ratio > 30; in aerobic rice soils), the methanotrophs may switch substrates from CH_4 to NH_4^+ (due to activity enzyme similarity), causing the inhibition of CH_4 oxidation in soil environment (Dubey 2003). Thus fertilizer N addition (preferably ammonium sulphate) often promotes the net gains of C accumulation from soil N enrichment by emitting less CH_4 from both aerobic and flooded rice soils by changing the soil pH (Chen et al. 1993). Small-scale field experimentation showed that if the organic manure application is replaced with equivalent amount of inorganic N fertilizers, then CH_4 emissions drop dramatically (Khalil and Butenhoff 2008).

3.3.12 Tillage

Scarce published data are available for studying the impact of tillage on CH_4 emission from rice soils. Spring ploughing positively influenced CH_4 emission (26%), as it changes soil physicochemical properties and eventually affect the decomposition of soil organic matter (Ko and Kang 2000). Most studies have found either no significant effect or a decrease in CH_4 emissions under conservation tillage practice (Ussiri and Lal 2009; Smith et al. 2010). However, long-term no tillage operation often lowers the dissolved organic carbon (DOC) content and facilitates higher bulk density, reduces the volume fraction of large pores and inhibits the decomposition of organic matter, thus having the potential to reduce the cumulative seasonal CH_4 flux from the surface soil layer of rice-based cropping system (Hanaki et al. 2002; Ahmad et al. 2009; Li et al. 2011). Under no till condition, the rice soils may act as a CH_4 sink that promotes the movement of CH_4 into oxidizing zones by sustaining greater pore continuity with high methanotrophic activity and greater rates of CH_4 diffusion into the soil profile due to increasing the compaction of surface soil layer (Smith et al. 2001). The CH_4 produced in the no tilled soil are entrapped in the soil for longer time period due to surface soil compaction that subsequently increases the probability of CH_4 oxidation by methanotrophic bacteria.

3.4 Response of Rice Ecosystem Towards the Projected Environmental Change

The environmental factors influencing the C_3 photosynthesis in rice canopy have indirect control on the CH_4 emissions and other associated ecosystem processes in wetland rice paddy soils under submergence with a variable degree of uncertainties (Prather et al. 1995). The projections of CH_4 emission from wetland rice ecosystem in the imminent future are a major concern under the combined increasing trend in atmospheric CO_2 concentration and rising temperature due to accelerated anthropogenic GHG emission-induced global warming. IPCC AR4 projections (2007) predicted the increase of global air temperature between 1.1 and 6.4 °C with a concomitant increase of atmospheric CO_2 level (~300 ppm) by the end of this century that is predicted to markedly modify the CH_4 emission dynamics from the submerged soils in wetland rice agriculture. CH_4 emissions from wetland rice paddy soils are generally a positive function of plant vigour and primary productivity that may be expected to increase due to enhanced rates of plant growth (more rice tiller numbers) through the enlargement of aerenchyma in a future enriched CO_2

environment (Aulakh et al. 2001a; Pereira et al. 2013). The available findings from the reported literatures, studying the trend and magnitude of changes in CH_4 emission from the lowland rice fields under elevated CO_2 combined with enhanced temperature conditions, are listed in Table 3.3, for a wide range of soil texture, rice cultivar and experimental CO_2 enrichment facility used. The vast majority of reported literatures suggests the potential of climate change, viz. atmospheric CO_2 enrichment and consequent temperature rise, to increase the global CH_4 flux from lowland rice fields. Both of these factors may affect soil biophysical characteristics and the activities of methanogens and methanotrophs in variable direction and magnitude (van Groenigen et al. 2011).

3.4.1 Impact of Elevated Temperature

Diverse responses of different ecosystems towards the global climate change has increased the difficulties to upscale the specific elevated temperature impact on methanotrophy at the global scale. Temperature plays a crucial role in CH_4 emissions from the anoxic soils, as the activities of both methanotrophs and methanogens are expected to be altered with rising temperature (Fey and Conrad 2003; Das and Adhya 2012). The mechanistic controls of elevated air temperature on the process-based growth response and CH_4 efflux from the anoxic submerged rice paddy soils are less known, inconsistent and often determined by the relative balance between contrasting possibilities under variable moisture availability (Singh et al. 2010; Gaihre et al. 2014). It is evident that the increase in air temperature has potential to exert a positive accelerating impact on CH_4 emission from the soil environment, but the trend is not universal. Rhizodeposition is the main origin of CH_4 evolved from rice fields (Kimura et al. 2004). Elevated temperature promotes soil organic matter decomposition, increases root exudation and sloughing with greater rhizodeposition (Allen et al. 2003; Das and Adhya 2012). The net impact has positive correlation with root biomass accumulation in rice (Aulakh et al. 2001a, b). Decomposition of organic materials in flooded rice fields generates CH_4 (Kimura et al. 2004). Thus, the elevated temperature-induced stimulation in CH_4 emission may be independent to the above-ground biomass accumulation preferably at the early stages of rice growth, viz. transplanting to panicle initiation, due to enhanced electron-donor production through hydrolysis and fermentation of organic matter that dominates over the temperature insensitive of Fe reduction rate in the submerged rice paddy soils (Tokida et al. 2010). Thus, the rising air temperature provides readily decomposable substrates for stimulating activities of the mesophilic methanogens, which thrive at optima between 30 and 35 °C (Minami and Neue 1994). The CH_4 production potential is unlikely to be a limiting factor within the specified temperature range. Despite the accelerating impact of elevated temperature on methanogenesis, laboratory incubation studies revealed the inhibitory effect of temperature on CH_4 oxidation process with a sharp decline in methanotroph abundance (Mohanty et al. 2007; Das and Adhya 2012). Temperature not only affected the activity but also changed the structure and the function (carbon and electron

Table 3.3 Interactive effect of elevated CO_2 and elevated temperature exposure on methane emission from wetland rice agriculture

Sl no.	Location	Cultivar	Facility used	Soil type	CO_2 elevation (ppm) over ambient	Temperature elevation over ambient (°C)	Associated increase in water/soil temperatures	% Increase in cumulative CH_4 production/emission			Source
								Elevated CO_2 effect	Elevated temperature effect	Additive effect (CO_2 and temperature) over ambient	
1	Florida, USA	IR72	Soil-plan-atmosphere research		350			+600			Baker et al. (1997a, b)
2	IRRI, Philippines (14°13’ N, 121°15′ E)	IR72	Open-top chamber		360	4 °C (Air)		+48.2 to +60	−47	+164	Ziska et al. (1998)
3	Florida, USA	Lemont and IR-72	Temperature gradient greenhouse tunnel	Arredondo fine sandy-loamy siliceous hyperthermicGrossarenicPaleudult	350			−76.6			Schrope et al. (1999)
4	Tsukuba, Japan (36°01’N, 140°07′E)	Nipponbare	Climatron facility		300			+23 to +145			Yagi et al. (2000)
5	Tsukuba, Japan (36°01’N, 140°07′E)	Nipponbare	Climatron facility		300			+58 to +65			Cheng et al. (2003, 2005)
6	Shizukuishi, Iwate, Japan (39°40’ N, 141°10′ E)	Akita Komachi	Free-air carbon dioxide enrichment	Andosol	200			+38 to +51			Inubushi et al. (2003)
7	Gainesville, Florida,USA	IR72	Soil-plant-atmosphere research (SPAR) chambers	Sandy, siliceous, hyperthermicUlticAlaquods	330	3 °C and 6 °C (Air)		+53.2	+19 (3 °C) to 209 (6 °C)	+258.4 (3 °C) to +402.4 (6 °C)	Allen et al. (2003)

8	Wuxi, Jiangsu, China (31° 37′N, 120° 28′E)	Japonica 99–15	Free-air carbon dioxide enrichment	Light clay-loam	200			+72 to +200			Xu et al. (2004)
9	Tsukuba, Japan (36°01’N, 140°07′E)	Nipponbare	Sunlit, semi-closed growth chambers in stainless steel containers	Alluvial soil	300			+28.6 to +56.3 (dissolved CH_4)			Li et al. (2004a, b)
10	Shizukuishi, Iwate, Japan (39°40’ N, 141°10′ E) & Wuxi, Jiangsu, China (31° 37′N, 120° 28′E)	Keng	Free-air carbon dioxide enrichment	Andosol and light clay-loam, respectively	200			+88			Zheng et al. (2006)
11	Tsukuba, Japan (36°01’N, 140°07′E)	Oryza sativa L., cv. japonica	Plant growth chamber	Alluvial soil	300			+58			Cheng et al. (2006)
12	Shizukuishi, Iwate, Japan (39°40′ N, 141° E)	Akita Komachi	Free-air carbon dioxide enrichment	Andisols	200			+6.3 (ns)			Cheng et al. (2008a)
13	Tsukuba, Japan (36°01’N, 140°07′E)	IR72	Controlled environment chambers	Grey sand soil	300	10 °C (Air) during night	~ 4.2 °C	+3.5 (ns) to +32	+35.1 to +71.4	+78.5	Cheng et al. (2008b)
14	Climatron facility, Shimadzu, Kyoto, Japan	Dular> IR-72 > IR65598 > Koshihikari	Plant growth chamber	Sandy soil	200			+10.9 to +23.8			Lou et al. (2008); Inubushi et al. (2011)

(continued)

Table 3.3 (continued)

Sl no.	Location	Cultivar	Facility used	Soil type	CO_2 elevation (ppm) over ambient	Temperature elevation over ambient (°C)	Associated increase in water/soil temperatures	% Increase in cumulative CH_4 production/emission			Source
								Elevated CO_2 effect	Elevated temperature effect	Additive effect (CO_2 and temperature) over ambient	
15	Shizukuishi, Iwate, Japan (39°38′ N, 140°57′ E)	Akitakomachi	Free-air carbon dioxide enrichment	Andosol	200	2 °C (Soil)		+ 26 to +28 (ns)	+44	+80	Tokida et al. (2010, 2013)
16	Gwangju, Korea (35°10’N, 126° 53′E)	lmybyeo	Temperature gradient field chambers	Loam	300	1.7 °C (Air)		+18	+8 (ns)	+29.3	Yun et al. (2012)
17	Jiangsu province-Yangtze River Delta, China (32°35′ N, 119° 42′E)	Wuxiangjing 14 (japonica)	Free-air carbon dioxide enrichment	Shajiang-AquicCambosols	200			+15 (ns)			Xie et al. (2012)
18	CRRI, Cuttack, India (20°27′N, 85°56′ E)	Naveen	Open-top chamber	Sandy clay loam-AericEndoaquept	156	2 °C (Air)		+24.3		+26.3	Bhattacharyya et al. (2013)
19	Salvaterra de Magos, Portugal (39°2.2015’N, 8°44.257’W)	Ariete	Open-top chamber	Clay loam-Anthrosols	175	3 °C (Air)	2 °C		+13.6 to +84.9 (ns)	+8.5 to +97.4 (ns)	Pereira et al. (2013)
20	Changshu, Jiangsu, China (31°30′N, 120°33′E)	Changyou 5	Free-air carbon dioxide enrichment	Gleyi-StagnicAnthrosol	110	2 °C (Air)		+23.7	+86.9	+56.6	Yang et al. (2015)

flow) of a complex methanogenic system in wetland rice ecosystem. The relative abundance of most frequent methanogenic groups, viz. Methanosaetaceae, decreased along with the increasing relative abundance of acetoclastic methanogens (Methanosaetaceae and Methanosarcinaceae) under elevated temperature (Fey and Conrad 2000). However, the potential C availability to methanogens from altered plant metabolism under elevated temperature dominantly governs the change in CH_4 flux from the submerged rice fields, rather than the changing soil bacteria dynamics preferably at panicle formation and grain-filling stages (Yun et al. 2012; Tokida et al. 2013). On the other hand, the excessive increase in air temperature stimulates plant respiration over leaf photosynthesis to a greater extent that reduces tillering, alters plant metabolic processes and increases floral/spikelet sterility at the reproductive phase (viz. booting, flowering), increasing disturbance during the grain-filling stage (Baker et al. 1997a, b; Gaihre et al. 2013). In contrary, elevated temperature-induced negative C balance in rice plants often reduces the potential C availability to methanogens and the net CH_4 emission as the recent photosynthates are the important source of C for methanogenesis in the submerged wetland rice ecosystem (Ziska et al. 1998; Cheng et al. 2008a; Yun et al. 2012). Hence, the relative change in CH_4 emission with elevated temperature regime often depends on the actual temperature range exposure. Under the low ambient temperature, CH_4 emission generally increases. While considering the high temperature range as ambient, the CH_4 emission may decrease, due to a combination of stress to the methanogens as well as the rice plants that act as conduits for CH_4 generated in wetland rice agriculture (Schrope et al. 1999; Gaihre et al. 2013).

Modelling studies predict 20% increase in net CH_4 emissions from rice paddies for +2 °C rise in temperature beyond the optimum temperature range (Li et al. 2004a). Global temperature rise of 3.4 °C unveils the possible increase in global CH_4 emission by ~78% (Shindell et al. 2004). Moreover, a sharp decrease in CH_4 emissions is obvious only when the air temperature goes beyond a certain threshold of 37 °C in laboratory experiment (Yang and Chang 1998; Cheng et al. 2000) and above 34.5 °C in the field soil temperature (Parashar et al. 1993). CH_4 transport capacity of rice plant is directly controlled by root-zone temperature rather than by air temperature. Increase in soil temperature has direct control on plant-root respiration, microbial activities and the steady-state CH_4 production rates in the soil environment, irrespective of air temperature (Fey and Conrad 2000). Therefore, the marginal increase in standing water/soil temperature within the optimum range of mesophile activity is crucial for methane emission from submerged rice paddy fields, and the air temperature rise should facilitate the plant photosynthesis to provide more C to methanogens via rhizodeposition. Otherwise, any increase in rhizosphere temperature may have the least impact on the methanogenesis as well as the CH_4 emissions from rhizosphere environment (Gaihre et al. 2014). A moderate increase in ambient air temperature by <2 °C over the average ambient air temperature (~24.8 °C) during the reproductive stage has negligible impact on the floral sterility and net CH_4 emission from wetland rice fields (Yun et al. 2012). However, more than 3 °C increase in air temperature drastically alters the plant metabolic processes, thereby reducing the net CH_4 flux from wetland rice agriculture (Ziska et al. 1998; Allen Jr. et al. 2003).

3.4.2 Impact of Atmospheric CO_2 Enrichment

Several mechanisms are proposed to explain the possible increase in the CH_4 emission from the submerged soils under wetland rice agriculture in the elevated CO_2 environment. The process of CO_2 enrichment within the canopy often concentrates CO_2 at Rubisco to enhance the catalytic turnover rate that further promotes the amount of CO_2 fixed per unit Rubisco protein from the enhanced rate of photosynthesis in C_3 rice (Cheng et al. 2006; Cheng et al. 2008a; Caemmerer and Evans 2010). Rice releases photosynthates into the rhizosphere (rhizodeposition), and they follow a different avenue of decomposition in soil. The higher photoassimilation under elevated atmospheric CO_2 increases primary productivity and promotes root growth, so as the belowground C allocation in the form of readily decomposable root-derived organic C substrates to the soil microbes (root exudates or root autolysis products) as well as the CH_4 production activity and the amount of CH_4 entrapped in the rice paddy soil over the entire course of the growing season (Ziska et al. 1998; Inubushi et al. 2003; Allen et al. 2003; Cheng et al. 2006; Lou et al. 2008). The easily enhanced decomposable energy-rich substrate availability may lead to a general increase of labile soil C and N pools (biological N fixation and N mineralization: Cheng et al. 2001) that ensures the fresh supply of C input for the stimulated growth, population and activities of heterotrophs and methanogens enhancing the seasonal CH_4 emission from the surface layer of tropical submerged lowland rice soils (Inubushi et al. 2001; Xu et al. 2004; Bhattacharyya et al. 2013, 2016). Atmospheric CO_2 enrichment hastens the significant population rise of methanogens (both acetoclastic and hydrogenotrophic) with subsequent decrease in soil redox potential and increased readily mineralizable C, along with the depressing effect on methanotroph population in laterite and alluvial soils under flooded rice paddy cultivation (Das and Adhya 2012). In contrast, the elevated atmospheric CO_2 level may have least impact on activity of methanogens (Cheng et al. 2000). However, Inubushi et al. (2011) observed the high dependency of CH_4 oxidation on microbial biomass C but no clear trend for elevated CO_2 impact on methanotrophs activity in flooded andosol fields under different rice paddy cultivars. Furthermore, the reduced transpiration from partial stomata closure inhibits leaf-level transpiration in the elevated CO_2 environment. The significant reduction in transpiration loss may result in greater soil moisture availability over a longer time period, which in turn will favour methanogenesis over methanotrophy, preferably after draining out of floodwater from the wetland rice fields (Singh et al. 2010).

Elevated CO_2 intensifies plant N uptake and, modifies N metabolism that amplies the population of ammonifiers, denitrifiers and nitrifiers in rice rhizosphere; thus reduces soil N availability to the methanotrophs. Therefore finally CH_4 oxidation process is inhibited (Bhattacharyya et al. 2013, 2016; Yang et al. 2015). However, the population of methanogen and methanotroph may not always be the only important decisive factors, so as their activity influencing the net CH_4 emissions under elevated CO_2 environment (Inubushi et al. 2003). The stimulatory effect of elevated CO_2 on CH_4 emissions from submerged wetland rice paddies may disappear from restricted plant growth due to limited N availability. Accumulative CH_4 emissions under the long-term elevated CO_2 exposure from the field under temperate rice-wheat sequence depend on periodic N fertilizer addition to the standing crop and the level of leftover residue availability from preceding crop (Inubushi et al. 2003; Zheng et al. 2006). In contrast, climate change factors are estimated to have least/negligible impact on the net CH_4 efflux from the upland rice ecosystem (van Groenigen et al. 2011).

Obviously, more extensive research experimentations are essentially required to understand the underlying mechanisms responsible for the large variation in the reported elevated CO_2 impact studies on CH_4 emission. In contrast to the reported increasing trend in majority, Schrope et al. (1999) observed a negative impact of elevated CO_2 environment on CH_4 emission from wetland rice. Despite a substantial increase in root dry matter and above-ground dry biomass accumulation, the CH_4 production in the rhizosphere was hindered, possibly due to the improvement of the O_2 supply into below-ground plant parts under enriched CO_2. The increse in aerobicity resulted in reduced CH_4 emissions from rice rhizosphere.

3.4.3 Interactive Impact of Elevated CO_2 and Air Temperature

A combined rise in atmospheric CO_2 and air temperature is the most expected projection, rather than a sole rise in any of these two factors for our future climate system. The stimulation of CH_4 emission under the combined impact of CO_2 elevation and temperature is conspicuous (Table 3.3). The net impact may be additive or nonadditive (Cheng et al. 2000; Yun et al. 2012; Pereira et al. 2013; Yang et al. 2015). Enhancement of CH_4 flux is often attributed to more C allocation of C to shoot, coarse or fine root biomass and C-rich metabolites, which in turn increases the TOC in root exudates and thus promotes the organic matter decomposition and the final rice grain yield (Roy et al. 2012; Bhattacharyya et al. 2013). Elevated CO_2 combined with elevated temperature also alters the soil N dynamics by stimulating mineralization of labile organic N and decreased mineralization of recalcitrant organic N, thus promoting the net microbial activity in the submerged paddy soils (Chen et al. 2016). The positive response of CH_4 flux under the interactive effect of elevated CO_2 and temperature accounts the significant amplification of acetoclastic and hydrogenotrophic methanogen population without affecting the CH_4 oxidation process (Das and Adhya 2012). Increased night temperature by 10 °C throughout the reproductive phase depressed the stimulatory effect of elevated CO_2 on CH_4 emission. High night temperature enhanced plant respiration and decreased C and N allocation to developing grains that failed to fulfill the increased sink demand from the rapid use of photoassimilates. However, such source-sink imbalance rarely contributed to the increase in final grain yield as well as CH_4 production process in rice rhizosphere (Cheng et al. 2008b, 2010).

3.4.4 Manipulative Role of Algal Population to Modify the CH_4 Flux Response Under Elevated CO_2 and Temperature from the Flooded Wetland Rice Agriculture

Enhanced algal growth on the floodwater in the wetland rice paddies promoted the CH_4 oxidation either by increasing O_2 supply in flooded water's surface that inhibited the CH_4 flux (ebullition or diffusion) through the water-air interface (Cheng et al. 2000, Inubushi et al. 2001) or by increasing the O_2 delivery to rhizosphere, resulting in the decrease in plant-mediated CH_4 transport to the atmosphere at early crop growth stages from flooded wetland rice under atmospheric CO_2 enrichment (Schrope et al. 1999). The effect of gradual increase in algal growth exerted less influence on internal CH_4 synthesis, with increased canopy cover and phonological advancement in rice. Therefore, the sole effect of elevated CO_2 on CH_4 oxidation process via increased algal growth is often negligible (Inubushi et al. 2003). However, the algal growth stimulation may dominate over other controlling factors to depress the net CH_4 emission considerably from wetland rice agriculture at early crop growth stages, preferably under the combined exposure of warmer air temperature and elevated atmospheric CO_2 concentration (Pereira et al. 2013).

At present, we are still far from being able to predict future CH_4 emissions, as the majority of impact assessment studies have been conducted under controlled condition and focused on the relative changes in CH_4 emissions in response to elevated CO_2 and warming exposure, rather than paying less attention to the mechanisms behind the net ecosystem response. The magnitude of the relative change of CH_4 emission (%) in the reported literature is drastic for the controlled environment experiments (growth chamber, greenhouses or closed sunlit chambers, OTCs) than open-field enrichment, as these experiments often overestimate the interactive impact of elevated CO_2 and temperature on the plant system (Yun et al. 2012; Bunce 2016).

3.4.5 Impact of Elevated Ozone

Rapid urbanization in the post-industrial revolution era accelerated air pollution and amplified the level of troposphere ozone that became an additional contributing factor to anthropogenic global climate change. Ozone is a short-lived secondary pollutant generated from the oxidation of emitted hydrocarbons. Elevated level of atmospheric ozone has an inexorable impact on rice ecophysiology and associated CH_4 emission dynamics from wetland rice cultivation. The reported literatures from the field-scale experimentation studying the elevated ozone impact on CH_4 emission from wetland rice ecosystem came into the public domain only after 2010. At present, there is still inconclusive evidence due to limited experimental reports on multifactorial elevated O_3 exposure impact on CH_4 emission from submerged wetland rice ecosystem. For ecosystem modelling studies, better scientific understanding of the ecosystem processes demands more elaborative field-level research experimentation on elevated O_3 impact in conjunction to elevated CO_2 and temperature enhancement factor, under diverse agroclimatic condition. In this section, we briefed on the available literatures studying the sole impact of elevated O_3 level on potential CH_4 emission from wetland rice paddies in the recent past.

Elevated ozone increased above-ground C demand with a significant reduction in below-ground C allocations in terms of root biomass, root activity and rhizodeposition across different rice cultivars (Andersen 2003; Emberson et al. 2009). The lower substrate availability reduced dissolved organic C content in soil solution and depressed the methanogenic bacteria population (archaeal communities) as well as inhibited their critical ecological functions for methanogenic activity in submerged rhizosphere environment of rice paddy (Bhatia et al. 2011). The abundance and diversity for the dominant groups of paddy methanogens, viz. aceticlastic Methanosaeta, were adversely affected under elevated O_3 exposure (Feng et al. 2013). Thus, a sharp decline in CH_4 emission from the submerged rice paddy is obvious under the elevated O_3 environment. Consequently, the draining out of stagnated water from submerged rice paddy fields promoted favourable conditions for the rapid growth of methanotrophs during the later crop growth stages under elevated O_3 environment. Thus, elevated O_3 exposure in submerged rice paddy resulted in the net CH_4 uptake (negative CH_4 flux) towards crop maturity (due to enhanced soil aeration) with a significant reduction in cumulative seasonal CH_4 emission (Bhatia et al. 2011, Zheng et al. 2011). Fresh supply of readily decomposable organic C from previous crop leftover often suppressed the depressing effect of short-term elevated O_3 exposure on root exudation and microbial proliferation in rhizosphere environment, without affecting net CH_4 emission from submerged lowland rice fields in the rotational rice-wheat cropping systems (Kou et al. 2015). Therefore, elevated O_3 exposures have partial potential to mitigate the global warming induced by soil carbon loss with decreased CH_4 emission.

3.5 Adaptation and Mitigation Options

For emission of the CH_4, three specific situations are required: (a) substrate, ample source of carbon, i.e. organic matter; (b) aeration status, anaerobic situation; Eh should be less than -200 mV; and (c) microbes, methanogens. Any method, which alter these three situations, may be considered as the adaptations and mitigations strategy to curb CH_4 emission.

(a) **Methods dealing with availability of substrate**

(i) ***Nitrogen availability:*** The application of N fertilizers needs major attention to control CH_4 emission in rice production. Several experiments were conducted to examine the effect of N fertilization on CH_4 emissions from paddy fields (Singh et al. 1999; Krüger and Frenzel 2003). As an outcome it was observed that the application of urea-based fertilizers increased CH_4 emission from rice fields. The probable reason was thought as inhibition of CH_4 oxidation and simultaneously the stimulation of CH_4 production as induced by nitrogenous fertilizers (Schimel 2000). In contrast to such results, reduction in CH_4 emission induced by nitrogenous fertilizers was also reported (Bodelier et al. 2000). When urea and other urea-based nitrogenous fertilizers are applied to the submerged rice soils, it hydrolyses to NH_4^+. The NH_4^+ ion imposes both positive and negative impacts on CH_4 emission through various means likely, (a) improving aerenchyma conduits through stimulating rice growth and more tiller number and enhancing CH_4 ebullition (increasing CH_4 emission), (b) providing more methanogenic substrates (add more litter, root exudates and root autolysis products) by improving growth and increasing root biomass of rice (increasing CH_4 emission; Inubushi et al. 2003), (c) stimulating the activity of the microbes responsible for decomposition (increasing CH_4 emission, Inubushi et al. 2003), (d) intensifying plant N uptake and thereby reducing the soil N availability and inhibiting the activities of methanotrophs towards the CH_4 oxidation (increasing CH_4 emission, Hütsch 2001, Xu et al. 2004), (e) increasing CH_4 oxidation by supplying more O_2 to the rhizosphere through enlarged aerenchyma conduits (decreasing CH_4 emission) and wider C/N ratio, and (f) hampering the decomposition of plant residues and, therefore, inhibiting CH_4 production as well as intensifying CH_4 consumption by stimulating the activities of methanotrophic bacteria (decreasing CH_4 emission, Cotrufo et al. 1998; Krüger and Frenzel 2003). Based on the balance of CH_4 formation or its oxidation, the increase or decrease of CH_4 emission has taken place.

(ii) ***Cultivar specificity:*** Rice varieties affect CH_4 emissions because of two reasons: (1) variation in the aerenchyma tissue which mediates the transportation of CH_4 and O_2 (Aulakh et al. 2000). The aerenchyma of rice paddy acts as a chimney to emit CH_4. Moreover, the well-developed airspaces in leaf blades, leaf sheath, culm and roots provide an efficient gas exchange between the atmosphere and the anaerobic soil (Neue and Roger 1994) and (2) provide substrates for methanogenic bacteria and methanotrophs through root exudates and/or dead root cells (Kerdchoechuen 2005). Therefore, variation in the cultivar may play a major role in the regulation of CH_4 emissions from rice fields, and this phenomenon has been widely studied (Setyanto et al. 2000; Wassmann et al. 2000b). Gutierrez et al. (2013) found that CH_4 emission differs significantly among cultivars but not between the late- and early-maturing groups. Hence, the selection and breeding of cultivars with lower CH_4 emissions and higher productivity are a promising strategy for minimizing CH_4 emissions instead of selection of early-maturing cultivars.

(iii) ***Land use (tillage/residue management):*** Conversion of upland to lowland cultivation of rice significantly affects the CH_4 emission through changing availability of electron donors, redox status of soil Fe and activity of methanogens, which ultimately resulted in low CH_4 emissions (Eusufzai et al. 2010). The land-use changes in natural or seminatural ecosystems such as peatlands reverting to forest (Ball et al. 2002) and upland grasslands becoming forest (Menyailo et al. 2008) result in net consumption of CH_4.

(b) Methods dealing with aeration status

(i) ***Water management:*** Like nutrient management, water management like alternate wetting and drying and midseason drainage is one of the most important factors controlling CH_4 emission from rice paddies (Zou et al. 2005). To reduce the water requirement of rice paddy, the International Rice Research Institute (IRRI) has proposed a 'safe alternate wetting and drying (AWD)' technique which may reduce CH_4 emissions by 70% (IRRI 2013). The AWD avoids occurrence of very low redox potential in soil and thus it can suppress CH_4 emissions. This technology involves frequent wetting and drying of soil in such a way so that the water level does not fall below a soil depth of 15. On the other hand, this kind of drainage may contribute greatly to increase N_2O emissions and might prevail over the benefit of reduced CH_4 emissions. Therefore, only safe AWD may not be much effective to reduce overall emission. Safe AWD in combination with straw biochar could be an effective strategy in suppressing overall emissions (Pandey et al. 2014).

(ii) ***Addition of Fe/Mn/S containing fertilizers*****:** CH_4 production requires carbon and electron flow to methanogens under strict absence of free oxygen. The main electron acceptors in submerged soils are dissolved oxygen (O_2), NO_3^-, Fe (III), SO_4^{2-} and CO_2. The end products of reduction in submerged soils are Fe (II) from Fe (III), H_2S from SO_4^{2-} and CH_4 from CO_2. External application or in situ availability of terminal electron acceptors such as Fe/Mn/S containing fertilizers allows iron or manganese or sulphate reducers to successfully compete for substrates (hydrogen or acetate) with methanogens (Sahrawat 2004). The concentrations of H_2 and acetate are depleted to so low levels that CH_4 production is not possible (Hori et al. 1993; Ratering and Conrad 1998). This hinders CH_4 production. Moreover these Fe/Mn/S containing fertilizers also oxidize CH_4 and reduce its emission. For example, addition of single superphosphate (contains sulphur) to flooded rice soils inhibited CH_4 production (Adhya et al. 1997).

(c) Methods dealing with microorganism

(i) ***Methanotrophy:*** In the nitrification-denitrification and sulphur oxidation-reduction, methanotrophy is one of the coupled reactions of methanogenesis which involves the conversion of methyl group to CO_2, using either oxygen or other compounds of higher oxidation status as electron acceptors. Methanotrophs are the bacteria which are able to grow using CH_4 and are part of a larger grouping of organisms that can utilize one-carbon (1-C) compounds having no C-C bonds. It is investigated that methanotrophic bacteria use molecular oxygen as the terminal electron acceptor and therefore are obligate aerobes, although there is evidence that certainly, sulphate (SO_4^{2-})-reducing habitats exist, in which anaerobic CH_4 oxidation occurs.

Methanotrophs oxidize CH_4 by first initiating reduction of an oxygen atom to H_2O_2 and transformation of CH_4 to methyl group (CH_3OH) using CH_4 monooxygenases (MMOs) (Krüger et al. 2003). Furthermore, two types of MMO have been isolated from methanotrophs: soluble CH_4 monooxygenase (sMMO) (type I) and particulate CH_4 monooxygenase (pMMO) (type II). Cells containing pMMO have demonstrated higher growth capabilities and higher affinity for CH_4 than sMMO-containing cell (Krüger et al. 2003). It is suspected that copper ions may play a key role in both pMMO regulation and enzyme catalysis, thus limiting pMMO cells to more copper-rich environments than sMMO-producing cells. Methanotrophs (methanophiles) metabolize CH_4 as their only source of carbon and energy. Aerobically or anaerobically, they require single-carbon compounds to survive. Under aerobic conditions, they combine oxygen and CH_4 to form formaldehyde, which is then incorporated into organic compounds via the serine pathway or the ribulose monophosphate (RuMP) pathway. Type I methanotrophs are part of the *Gammaproteobacteria* which they use in the RuMP pathway to assimilate carbon. On the other hand, type II methanotrophs are part of the *Alphaproteobacteria* and utilize the serine pathway of carbon assimilation. They also characteristically have a system of internal membranes within which CH_4 oxidation occurs. Methanotrophs occur mostly in soils and are especially common near environments where CH_4 is produced. Their habitats include oceans, mud, marshes, underground environments, soils, rice paddies and landfills. They are of special interest to researchers studying global warming, as they are significant in the global CH_4 budget (Oremland and Culbertson 1992; Holmes et al. 1999).

Methanotrophs, obligatory aerobic autotrophic organisms, which are abundant in oxic sites, standing water, surface soil and rice rhizosphere, oxidize CH_4 to carbon dioxide deriving energy from this reaction. Planktophytes, mainly consisting of microalgae, hold promise as efficient contraptions for harvesting greenhouse gases such as CO_2, because of their autotrophic mode of nutrition and ability to scavenge pollutants from the environment. In this context, it would be interesting to study the role of cyanobacteria and *Azolla* (a water fern harbouring a cyanobacterium, *Anabaena azollae*, commonly found as floating assemblages in rice paddies) in the CH_4 production-oxidation processes. During photosynthesis oxygen released by cyanobacteria into the standing water can diffuse into the soil and provide aerobic conditions, which is not congenial for methanogenesis. Alternatively, oxygen, released by cyanobacteria, can promote the proliferation of CH_4-oxidizing bacteria (methanotrophs).

Oxygen concentration in rice field with flooded water normally varies between 4 and 6 $\mu g\ g^{-1}$ (Mandal 1961; Saito and Watanabe 1978), and in the presence of profuse growth of cyanobacteria, concentration of oxygen in the water may reach 10–12 $\mu g\ g^{-1}$ (Mandal 1961; Lakshmanan et al. 1994). The effect of cyanobacteria in decreasing concentration of CH_4 may be due to enhanced CH_4 oxidation mediated by methanotrophs at high concentration of oxygen produced during their growth. The striking decrease in CH_4 concentration with living cells of *Synechocystis* species under light, but not under dark, would suggest that living cells of the cyanobacterium during photosynthesis under light provided oxygen for the proliferation of methanotrophs and thereby helped in accelerating the CH_4 oxidation by the methanotrophs.

(ii) ***Aerobic methane oxidation:*** Monooxygenase enzyme is responsible for the initial step in oxidation of CH_4 which requires molecular oxygen. The product of this reaction, methanol, is further successively oxidized via formaldehyde to formate and CO_2. Some of these intermediates may leak or be excreted from cell and perhaps support growth of other bacteria. The use of enzymes known as CH_4 monooxygenases to catalyse the oxidation of CH_4 to methanol is a defining characteristic of methanotrophs. The common metabolic pathway branches off, depending upon the type of methanotrophs, the monooxygenase involved, the metabolism of substrates by methanotrophs, the central role of formaldehyde as an intermediate in catabolism and anabolism and the unique pathways employed for the synthesis of intermediates of central metabolic route. Formaldehyde is usually assimilated further either through RuMP pathway or serine pathway. Methane monooxygenases present in aerobic methanotrophic bacteria exhibits a striking lack of substrate specificity that often results in the fortuitous metabolism of a very large number of compounds including xenobiotic chemicals. Thus catalysing a large number of biotransformations; methanotrophs have attracted the interest of scientists involved in the development of bioremediation technologies and in the use of bacteria containing methane monooxygenases for the production of chemicals with commercial value. Integration of the duck rearing reduces the possibility of CH_4 emission from the wetland rice ecosystem. Frequent activities of ducks often increase dissolved oxygen concentration in the standing water that eventually increases soil Eh value (depressing methanogenesis) and rapidly promotes the activity of methanotrophs in the wetland rice-duck complex ecosystem (Huang et al. 2005).

(iii) ***Inhibitor of methane reduction bacteria:*** Dicyandiamide (DCD) inhibits CH_4 production in a flooded alluvial soil due to higher redox status, lower pH, lower Fe^{2+} and readily mineralizable carbon contents as well as the lower methanogenic bacteria population and their activity (Bharati et al. 2004). Thus, the pattern of CH_4 production following repeated addition of DCD might have resulted from enhanced methanogenesis by higher NH_4^+ concentration, due to inhibition of nitrification and DCD degradation from its repeated application and continued inhibition of methanotrophs. In DCD-retreated soils, however, the redox potential was lower than that of control. Soil pH was also high in DCD amended soils. Soil alkalinity further increases CH_4 production in presence of NH_4^+, being accumulated due to inhibition of nitrification process (Joseph and Prasad 1993).

The amount of acetate-derived methanogenesis can be assessed with methyl fluoride, fluoromethane (CH_3F), a specific inhibitor for aceticlastic methanogenesis when applied in microbial ecology; CH_3F was assumed to be a specific inhibitor for

CH_4 oxidation and ammonium oxidation (Oremland and Culbertson 1992; Bodelier and Frenzel 1999). While providing direct access to processes, inhibitor experiments may be misleading, if specificity is confined to certain conditions (Oremland and Capone 1988). Indeed, CH_3F turned out to be an efficient inhibitor of methane and ammonium monooxygenases.

Sodium azide inhibited CH_4 production by 75% over that of unamended control. Sodium azide, a potent nitrification inhibitor, is also a respiratory inhibitor and a microbial inhibitor and is known to increase N_2O emission in soils (Aulakh and Rennie 1985). Although ammonium thiosulphate and thiourea stimulated CH_4 production, especially at 40 days of incubation, CH_4 production was observed lower than the unamended control. Nitrogen-containing compounds are known to stimulate CH_4 production in flooded soils (Bollag and Czlonkowski 1973).

3.6 Summary

Despite the large variation in the available literatures, taken together, the trend for the potential increase in accelerated CH_4 emission from the wetland rice paddy is evident under the projected combined increase in atmospheric CO_2 and air temperature by the end of the twenty-first century. Thus, the possible consequences of the rising CO_2 and subsequent warming of our atmosphere may be a reduction in the soil CH_4 sink strength in submerged rice paddy that may act as a positive feedback to the greenhouse effect, thereby exacerbating the global climate change.

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4 Response of Soil Properties and Soil Microbial Communities to the Projected Climate Change

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Abstract

With the advancement of human civilization, anthropogenic emission of greenhouse gases induces climate change. Science has made significant development in evaluating the direct and indirect impacts of climate change on the most important natural resource, the soil. The variable magnitude of emitted GHG fluxes between the soil and the atmosphere is primarily sourced from soil microbial activity that is mostly regulated by the existing soil environment. Certain soil properties, fertilizer nutrient management, and water management practices influence the magnitude of soil GHG fluxes. This chapter focuses on the impact of changing climatic variables on the dynamics of carbon and other major nutrients and micronutrients and deals with the effect of climate change on the processes that alter their cycling and availability. The changing environmental variables will most likely impact on nutrient transformation in soil and also alter its plant availability dynamics. The nutrients like C and N are controlled by biological cycles and may show a different reaction to the changing climatic variables than the elements with cycles controlled both by geological and biological processes, such as P, S, and K, or elements with predominantly geologically controlled cycles, such as K, Ca, Mg, S, or micronutrients. In this chapter, we also review how the soil microbial community and the extracellular enzymes are affected by alteration of the climate. The diversity and composition of the aboveground plant community influences the soil microbial community through the supply, timing, and composition of residues and exudates. There are many reports showing

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evidence that environmental modifications (increase in temperature, elevated carbon dioxide, drought, excess moisture, etc.) significantly impact the abundance, diversity, and activity of soil biota. Besides, we briefly focus on how greenhouse gas emissions are influenced by different soil characteristics. We have highlighted the global carbon pools and soil carbon pools. Actually, soil organic carbon (SOC) pool is 20.99 Pg up to 30 cm depth and 63.19 Pg up to 150 cm depth of soils in India, and the highest SOC pool was observed in aridisols followed by inceptisols and alfisols. Understanding the characteristics of these pools helps to apprehend the global climate change more clearly. Even with the paucity in availability of literature, we have also discussed the effect of environmental modifications/change on soil physical properties. With the current knowledge regarding climate change, the adaptation and mitigation of the climate change are also addressed.

Keywords
Carbon pools · Climate change · Climatic variables · Greenhouse gas · Soil biodiversity · Soil enzymes · Soil properties

4.1 Introduction

In the present century, accelerated anthropogenic emission is accountable for the global climate change. The climate change affects the Earth's physical, biological, and ecological systems and becomes a major environmental concern. Due to rapid urbanization and industrialization in the post-industrial revolution era, emission of greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3) increased at an alarming rate into our atmosphere with ever-increasing world population (Wang et al. 1976; Chatterjee and Saha 2015). These increases are attributed mainly to extensive fossil fuel usage, land-use change, and intensive agriculture. Ammonia does not impose any direct effect on global warming. However, about 10% of atmospheric ammonia is oxidized to NO and NOx, which play a catalytic role in several photochemical reactions in which O_3, CH_4, CO, and OH are involved. Tropospheric O_3 is mostly produced by light-catalyzed reactions involving nitric oxide (NO) and organic compounds (e.g., isoprene, monoterpenes) emitted by vegetation, further contributing to atmospheric warming (García-Marco et al. 2014). Non-methane hydrocarbons are also oxidized by tropospheric O_3 to CO in the atmosphere that subsequently converted into CO_2. By far, three major GHGs, viz., CO_2, CH_4, and N_2O, are coming from soil and agriculture-related sources. Due to their relatively long atmospheric residence times, CO_2, CH_4, and N_2O have important effects on the radiative balance. Despite very low concentration of CH_4 and N_2O, they are estimated to have a disproportionately larger effect than atmospheric CO_2 in the radiative forcing because of their global warming potential (Table 4.1).

In this section, we will confine our discussion for these three major GHGs. Agricultural GHG fluxes are complex and heterogeneous, and historically,

Table 4.1 Residence time, radiative absorption potential of different GHGs in atmosphere

Greenhouse gases	Residence time (yr)	Radiative absorption potential*
Carbon dioxide	100	1
Methane	12	23
Nitrous oxide	114	298
Ozone	0.1–0.3	2000
Chlorofluorocarbons (CFCs)	65–110	> 10,000

*CO_2 as reference

Table 4.2 Relative contribution of different GHGs (%) to the anthropogenic warming

Greenhouse gases	% Contribution
Energy-related carbon dioxide	81.3
Methane	10.5
Nitrous oxide	4.3
Carbon dioxide from other sources	1.5
Chlorofluorocarbons (CFCs)	2.5

agricultural soils have been a major source of large amounts of C and N to the atmosphere. To account their warming potential, the non-CO_2 emissions are always expressed in CO_2 equivalents (CO_2-eq). Agriculture is a net source of GHG contributing about 10–12% (5.1–6.1 Pg CO_2-eq year^{-1}) of total GHG emissions worldwide. These emissions are mostly in the form of methane (CH_4) (up to 3.3 Pg CO_2-eq year^{-1}), nitrous oxide (N_2O) (up to 2.8 Pg CO_2-eq year^{-1}), and carbon dioxide (CO_2) (IPCC 2007a, b). Nitrous oxide is produced and emitted into the atmosphere by nitrification, incomplete denitrification, nitrifier denitrification, and/or fungal denitrification, as well as during reduction of nitrate (NO_3^-) to ammonium (NH_4^+) (Kool et al. 2010). Methane is formed by methanogenic microorganisms in anaerobic microsites and consumed by soil methanotrophs, especially in aerobic microsites (García-Marco et al. 2014). The relative contribution of different GHGs to the anthropogenic warming to the Earth's atmosphere is listed in Table 4.2 (EIA 2008).

Being the major contributor to anthropogenic warming, about 24% rise in atmospheric CO_2 since the industrial revolution took place at 2.04 ppmv in the last decade compared to 0.84 ppmv during the 1960s (Saha et al. 2015). Among the most important GHGs, CH_4 ranks next to CO_2. The atmospheric CH_4 concentration also increased to 1.78 ppmv from its preindustrial concentration of 0.7 ppmv with a growing rate of 3% per year against 1.2% in the late 1970s (Pathak et al. 2003). Currently, the atmospheric concentration of N_2O is increasing at 0.8 ppbv per year (WMO 2011). The Intergovernmental Panel on Climate Change's Fourth Assessment Report (AR4), issued in February 2007, states that "most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic GHG concentrations." As atmospheric GHG concentrations increase, they will trap more outgoing long-wave radiation from the Earth's surface in the lower atmosphere. Thus, the excess trapped heat is expected to warm the oceans over several decades and that will in turn lead to a long-term change in our climate system. The magnitude of rise in Earth's ambient air

Table 4.3 Projected global average surface warming at the end of the twenty-first century

IPCC scenarios[a]	Temperature change (in °C in 2090–2099 as compared to 1980–1999)	
	Best estimate	Likely range
A1T (600 ppm)	+2.4	1.4–3.8
A1B (800 ppm)	+2.8	1.7–4.4
A2 (1250 ppm)	+3.4	2.0–5.4
A1F1 (1550 ppm)	+4.0	2.4–6.4

[a] Projected atmospheric CO_2 concentration in parenthesis IPCC (2007a, b)

temperature due to this human-induced emission of heat-trapping gases into the atmosphere was variable at both spatial and temporal scale. Hulme and Jenkins (1998) reported about 0.6 °C increase in air temperature over the past 100 years. The Intergovernmental Panel on Climate Change (IPCC) reported a linear increase in global surface temperature between 1906 and 2005 at the rate of 0.74 °C (range 0.56–0.92 °C), with a more rapid warming trend over the past 50 years. According to future projections generated by the current model simulations under variable levels of GHG emission scenarios, a substantial warming of our atmosphere (between 2 and 4 °C) may occur that is expected to induce many unexpected changes in the behavior of our global climate system during the twenty-first century in a greater magnitude than those observed during the past twentieth century with reduced weather predictability (IPCC 2007a, b). The details of IPCC projections for an increase in mean Earth surface air temperature under different projected atmospheric CO_2 level are listed in Table 4.3.

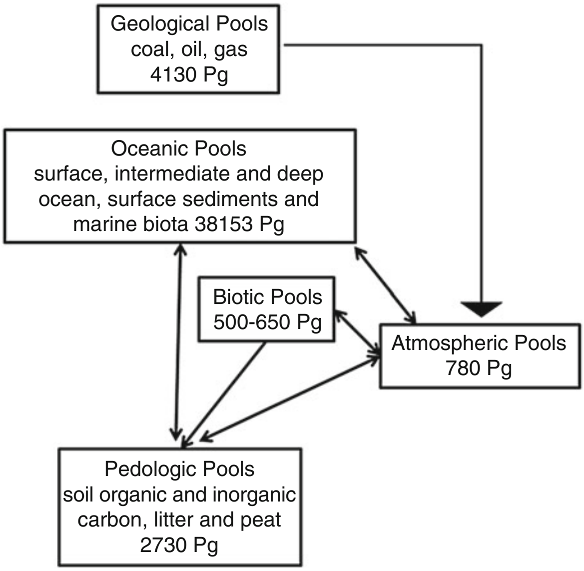
Over the time span of our Earth's history, the anthropogenic activities along with changes in our climate system often modified the physical and biogeochemical processes in soil, which resulted in a dynamic shift in the aboveground and belowground natural interactions within all of our existing terrestrial and aquatic agroecosystems across the world (Grieve 2001). Bidirectional interactions between the soil and climate of any agroecological unit mostly emphasize on the direct impact of soil processes on the changes in atmospheric composition through balancing between the production-consumption dynamics of different GHGs (viz., CO_2, CH_4, and N_2O) evolved through several physical and biochemical reactions and indirectly through the maintenance of production-consumption dynamics of NH_3, NOx, and CO within the soil environment. Both the climate changes and variability are likely to have significant short- and long-term impacts on soil properties. Although fossil fuel combustion is the primary source of CO_2 emission, land-use changes and conversion of forest and grasslands to agriculture (especially the rice cultivation) have also contributed significantly to rise in atmospheric CO_2 level. Alteration in land-use management may promote net CO_2 uptake and sequestration from the atmosphere. About 30% of CH_4 and 70% of N_2O are produced in the soil, and soil processes will control the future changes in the atmospheric concentration of these gases (Mosier 1998). The soil-atmosphere exchange of these GHGs is interrelated and regulated by the existing climatic condition. Changes in one cycle can impart significant modification for the other in the soil environment (C, N, and P cycling) that further influence the soil processes through additionally imposed changes in soil temperature, soil water, and nutrient competition under modified environmental condition. Regional-scale impact studies to measure the absolute amount and predict the changes in GHG fluxes are difficult due to high spatiotemporal variability of GHG fluxes.

The world population will increase from 6.8 billion in 2008 to greater than 9 billion in 2050 (United Nations 2008). There are very limited scopes to attain the sustainability in the increasing food production to feed the ever-increasing human population with the serious threat of soil degradation for many of the world's best agricultural soils (Cassman et al. 2003; Godfray et al. 2010). Intensive agricultural practices along with the excessive tillage, imbalanced nutrient application, and pesticide usage to meet growing demand for agricultural products have stressed the long-term sustainability of cultivated soils and pose a greater risk for deteriorating environmental quality (soil water and air) as well as overall ecosystem health. In this section we have emphasized the possible impact of this environmental change, viz., increasing concentration of atmospheric GHGs, temperature rise, etc., on soil health and gaseous exchange processes within the soil-plant-atmosphere continuum.

4.2 Soil Carbon Pools and Their Possible Role in Climate Change

Global carbon pools are subdivided into five major pools (Fig. 4.1, modified after Lal 2008). Among them, the largest is the oceanic pool which is estimated at 38,153 Pg, of which surface ocean contributes 900 Pg, intermediate and deep oceans contribute 37,100 Pg, surface sediments contribute 150 Pg, and marine biota contributes 3 Pg carbon. The second largest pool is the geological C pool which is estimated at 4130 Pg. This pool comprises fossil fuels, of which 84.99% is coal, 5.57% is oil, 3.39% is gas, and 6.05% is others (Lal 2008). This carbon pool is depleting through fossil fuel combustion at the rate of 7.0 Pg year^{-1} (Bandyopadhyay 2012). Pedologic pool is the third largest pool, which is estimated at 2730 Pg up to 1 m depth. This pool includes four components: soil organic carbon (SOC, 1550 Pg), soil inorganic carbon (SIC, 950 Pg), litter (40–80 Pg), and peat (150 Pg; Lal 2008). Soil organic carbon (SOC) pool is the largest terrestrial pool of carbon and plays a key role in carbon cycle and is, thus, the most vital pool for global climate change. Carbon is taken out in the form of CO_2 from the atmosphere by plant during photosynthesis. The carbon, thus fixed by plants, is transferred to the soil in the form of dead plant residues. These residues act a substrate for soil biota which decomposes and respires back to the atmosphere as CO_2 and CH_4. The soil inorganic carbon (SIC) pool includes elemental C and carbonates of minerals such as gypsum, calcite, and dolomite and comprises primary and secondary carbonates (Bandyopadhyay 2012). The atmospheric pool is the fourth largest pool (780 Pg), and it is increasing at a rate of 4.1 Pg year^{-1}. The least among the global pools is the biotic pool, estimated in the range of 500–650 Pg. The sum of the pedologic and the biotic pools are called the terrestrial carbon pool. There is more interaction in

Fig. 4.1 Global C pools (modified after Lal 2008)



between the terrestrial and the atmospheric pools (Fig. 4.1). The annual rate of global primary production (GPP) is 120 Pg, while the respiration is 60 Pg of carbon. Land-use conversion (1.1–2.2 Pg year^{-1}), decomposition (60 Pg year^{-1}), and soil erosion (1.1 Pg year^{-1}) caused the depletion of the terrestrial C pool and also the enrichment of the atmospheric pool. The fossil fuel (coal, oil, and gas) combustion depletes the geologic pool and enriches the atmospheric pool at the annual rate of 1.5–3 Pg carbon. The terrestrial sink is presently increasing at a rate of 2–4 Pg C year^{-1} and it may increase to approximately 5 Pg C year^{-1} by 2050 (Bandyopadhyay 2012).

Soil organic matter (SOM) is the dark-colored organic constituent of the soil which comprises of tissues from the dead plants and animals at various stages of decomposition mediated by soil biota. Undecomposed materials on the surface of the soil (e.g., crop residues) are usually more than 2 mm in size and are not considered to be part of the SOM (Corsi et al. 2012). The SOM comprises a mixture of (i) residues of plant and animal at various stages of decomposition, (ii) substances that are formed from the breakdown products through chemical and/or microbial synthesis, and (iii) the bodies of live microorganisms and small animals and their decomposing products (Schnitzer 1991). It is the well-decomposed product of the decomposition of organic materials; hence it is generally rich in more resistant compounds (e.g., lignin, cellulose, hemicelluloses, etc.) and poor in less resistant compounds (e.g., carbohydrates, polysaccharides, etc.) (Munda et al. 2018). Soil organic carbon (SOC) is the carbon occurring in the SOM. On average SOC constitutes about 58% of SOM mass. Soil organic carbon pool consists of three different pools (Table 4.4) based on its mean residence time (Jenkinson and Raynor 1977, Parton et al. 1987). Mean residence time means the time it takes to turn over and also it indicates its resistance to decay and the extent of protection against decomposition (Nayak et al. 2012).

Lal (2004) estimated the soil organic carbon (SOC) pool of 20.99 Pg up to 30 cm depth and 63.19 Pg up to 150 cm depth of soils (Fig. 4.2). The data are estimated from Walkley and Black oxidizable organic carbon measurement through approximation. The highest SOC pool was observed in aridisols followed by inceptisols and alfisols. The SOC pool in soils of India is 2.2% of the world pool for 1 m depth and 2.6% to 2 m depth (Lal 2004).

4.3 Soil Greenhouse Gas Emission: A Function of Soil Characteristics

Increase in concentration of atmospheric GHGs has hastened the rate of anthropogenic climate change over the last 50 years that may result in positive changes in the Earth's energy balance (Swain et al. 2018a, b; Chatterjee et al. 2018b). The variable magnitude of emitted GHGs fluxes between the soil and the atmosphere is primarily sourced from soil microbial activity that is mostly regulated by the existing soil environment. Certain soil properties, fertilizer nutrient management, and water management practices influence the magnitude of soil GHG fluxes. A significant positive feedback effect of global warming on soil GHG emissions is expected to further accelerate the warming process of our future world climate with an amplified magnitude.

4.3.1 CO_2 Emission

After photosynthesis, CO_2 flux from soil remains the second largest carbon (C) flux in most ecosystems and can account for 60–90% of total ecosystem respiration (Kuzyakov 2006). The soil CO_2 emission mostly relies on the microbial and root respiration at the soil surface or within the thin upper layer of the soil. Consequently the CO_2 uptake during photosynthesis balanced this CO_2 emission via carbon cycling pathways within our agroecosystems. The amount of global net CO_2 emissions is almost negligible (~0.04 Gt CO_2-eq year^{-1}) from the agricultural soils (excluding energy use in agriculture sector, IPCC 2007a, b). In general, soil CO_2 flux can be an indicator of microbial activity during the oxidation of organic matter. But, as compared to other GHGs (CH_4, N_2O), total CO_2 effluxes are not only solely derived from soil. Therefore, it is very difficult to determine whether the soil is a net source or net sink for atmospheric CO_2. Major sources of CO_2 efflux from soil include microbial decomposition of soil organic matter (SOM), rhizodeposit derived from living roots, residue decomposition, and root respiration. The magnitude and variability of soil-surface CO_2 efflux are controlled by several factors:

4.3.1.1 Weather Factor

Rainfall patterns strongly affected the spatiotemporal pattern of the CO_2 production rates throughout the soil profile by modifying the soil moisture status (discussed later).

Table 4.4 Different pools of soil organic carbon

Characteristics	Soil carbon pools			Reference
	Active or labile	Slow or an intermediate pool	Passive or stabilized	
Composition	Microbial biomass, their metabolites, and easily decomposable compounds (e.g., proteins and polysaccharides), root exudates	Structural plant residues and physically stabilized C	Mineral stabilized aliphatic compounds or complex aromatic structure	Jha et al. (2012)
Fractions associated with the pool	Soil microbial biomass carbon (SMBC) Water-soluble carbon (WSC) Acid-hydrolyzable carbohydrate (AHC) Dissolved organic carbon (DOC)	Readily mineralizable carbon (RMC) Light fraction carbon (LFC) in soil aggregates Particulate organic matter carbon (POMC)	Humic acid (HA) Fulvic acid (FA) Clay organic complex	Bhattacharyya and Manna (2014)
Type of protection	Not stabilized, easily accessible	Physical protection	Chemical stabilization or stabilization by organo-mineral bonding, biochemical stabilization	Sollins et al. (1996), Wander (2004)
Mean residence time	Few days to few years	10 to more than 100 years	1000 years	Paul et al. (2001), von Lützow et al. (2006)
C/N ratio	5–15: 1	20:1	7–9:1	Bhattacharyya and Manna (2014)
Availability to the microbes	Easily available	Slowly available	Resistant to oxidation and relatively unavailable	Wander (2004), Bhattacharyya and Manna (2014)
Temperature sensitivity	Less sensitive to an increase in temperature	Medium sensitive to an increase in temperature	Highly sensitive to an increase in temperature	Leifeld and Fuhrer (2005)

(continued)

Table 4.4 (continued)

Characteristics	Soil carbon pools Active or labile	 Slow or an intermediate pool	 Passive or stabilized	Reference
Major role in soil	Serves as a food and energy source for the living soil biological community Act as a buffering agent and useful in replenishment mechanism like desorption of soil colloids, dissolution of litters, etc.	Strong response to management, such as tillage, residue handling and levels, and crop rotation Key attribute in soil quality; it is the precursor of active pool	Contributes to cation and anion exchange capacity Prevents plant nutrients from leaching Modifies and stabilizes toxic materials Enhances soil aggregation	Overstreet and DeJong-Hughes (2015), Bhattacharyya and Manna (2014)

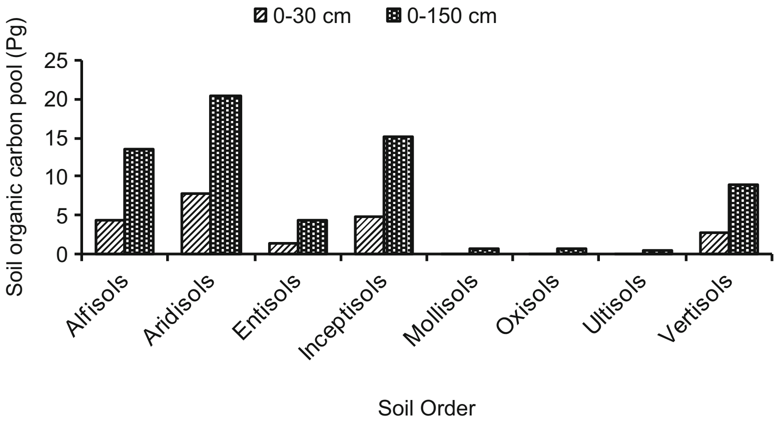


Fig. 4.2 Soil organic carbon pool in soils of India

4.3.1.2 Soil Temperature

Any change in air temperature modifies the soil thermal regime both in spatial and temporal domain and predominantly affects the spatiotemporal pattern of soil CO_2 evolution rate from soil. Soil respiration rate increases exponentially with increase soil temperature that enhanced CO_2 evolution. The increased rate of soil respiration with temperature slows down gradually at very high temperature exposure (Fang and Moncrieff 2001; Nosalewicz et al. 2013). Under sufficient moisture supply, CO_2 evolution almost ceased at <10 °C followed by a logarithmic increase between 20 and 40 °C; > 50 °C, it declined rapidly due to partial inhibition of microbial respiration due to inactivation of biological oxidation systems (Rastogi et al. 2002). The Q_{10} of soil CO_2 evolution value is estimated to be about 2 (Bouma et al. 1997). The rate of CO_2 evolution rises exponentially with increase in soil incubation temperature from 4 to 40 °C (Sato and Seto 1999). Soil temperature > 30–35 °C tends to limit CO_2 emissions because soil water becomes often limiting at those high temperatures (Wardle and Parkinson 1990).

4.3.1.3 Soil pH

The adverse effect of low pH on soil microbial activity contributes to lower microbial respiration rate in acid soil and consequently lower CO_2 evolution. Increase in soil pH up to 7.0 increases CO_2 emission, but when it goes beyond 7.0, the increasing alkalinity adversely affected CO_2 emission (Rastogi et al. 2002).

4.3.1.4 Soil Texture

Soil texture influences the water infiltration and gas diffusion rates within the soil environment that further modifies the CO_2 formation and emission process. CO_2 emission rate is significantly higher from clay soil than sandy soil (Kowalenko and Ivarson 1978; Sugihara et al. 2012).

4.3.1.5 Soil Moisture

Soil moisture from rainfall or applied irrigation is very useful to maintain the heterotrophic activity in this soil. Increasing soil moisture increases soil CO_2 emission up to an optimum level, but beyond that it has limited or often reduced effect on soil CO_2 emission (Drewitt et al. 2002). Soil respiration increases with increase in soil moisture between 40 and 70% water-filled pore spaces (WFPS) in most of the soils (Doran et al. 1990). At lower WFPS, soil respiration was reduced considerably by water availability, whereas at higher WFPS CO_2 production decreased as a result of reduced aeration. Increasing level of soil moisture results in small quantity of CO_2 emission but for prolonged duration as a result of the reduced gas exchange (Rusera et al. 2006). Alternate drying-wetting cycles enhanced dissolved organic carbon (DOC) production which increases microbial C consumption and enhanced O_2 consumption which also stimulates denitrification (Kalbitz et al. 2000).

4.3.1.6 Soil Trafficking/Soil Compaction

The relationship between soil respiration and WFPS is moderately influenced by the existence of macropores. Soil compaction in the inter-row soil often destroys the soil macropores and modifies the soil moisture levels above 70% WFPS, therefore enhancing the net CO_2 emission rates (Rusera et al. 2006).

4.3.1.7 Soil Salinity

Increasing soil salinity has adverse effects on physicochemical and microbiological processes in soil that affect organic matter decomposition. CO_2 evolution decreases with increase in soil salinity suggesting an increased osmotic stress on the soil microbial communities causing a reduction in their activity (Pathak and Rao 1998; Reddy and Crohn 2014). However, saltwater intrusion into freshwater wetlands with high organic matter, often suppressing the detrimental effect of salinity, increases soil respiration and promotes CO_2 emissions from wetland ecosystem (Weston et al. 2011).

4.3.1.8 Water Table Depth

More oxidized conditions associated with low water tables (> −20 cm) favor CH_4 oxidation by aerobic methanotrophic bacteria (Whalen 2005), as well as aerobic decomposition of organic matter, both processes emitting CO_2 from the soil environment (Olsson et al. 2015).

4.3.1.9 Crop Specificity

The seasonal and annual rate of CO_2 emission is one of the most determining factors for the annual rates of soil C cycling through autotrophic root respiration and heterotrophic microbial respiration as driven by annual soil C inputs (West and Marland 2002; Lee et al. 2009). As root activity has strong effect on spatiotemporal variability of CO_2 emissions (Rochette et al. 1991), higher soil CO_2 flux is usually expected in the rows relative to the inter-rows due to a higher root density during the crop growing season (Lee et al. 2009). The soil CO_2 emission follows the order of maize > cowpea > rice (Neogi et al. 2014).

4.3.1.10 Tillage

Higher turnover rate of organic matter after tillage promotes oxygenation in soil environment and increased soil CO_2 emissions due to degassing of dissolved CO_2 from the soil environment (Lee et al. 2009; Neogi et al. 2014). No-tillage or reduced tillage increases soil organic matter (SOM) reserve with the passage of time, available water content, and soil aggregation (Pare et al. 1999). Therefore, soils under conservation tillage practices (no-tillage or reduced tillage) may emit low CO_2 (Sanchez et al. 2002). But the effect of no-tillage on net soil CO_2 emissions is short-lived and often nonsignificant, when assessed under long-term scale (Lee et al. 2009).

4.3.1.11 Addition of Organic Material

Organic manure addition along with other organic wastes enhances the supply of soluble organic C into soil as a fresh substrate for growing microorganisms with their enhanced activity and increased soil respiration, which in turn emits more CO_2 from the soil environment by a factor of 2–3 (Rastogi et al. 2002).

4.3.1.12 Fertilizer Application

The effect of fertilizer N application on soil CO_2 emission is highly variable and site-specific (Pathak et al. 2016). Nitrogen application may decrease soil respiration and often resulted in a reduction of both emission rate and season-long cumulative emission of CO_2 from soil due to induced soil acidity with reduced soil pH (Al-Kaisi et al. 2008). In contrast, application of inorganic N may have little effect on CO_2 emission due to insensitivity of fertilizer N application toward the net N mineralization (Carpenter-Boggs et al. 2000).

Table 4.5 Factors and their most likely effect on CO_2 emission with confidence level

Factors	Most likely effect on CO_2 emission	Confidence level
Increasing soil clay %	↑	High
Low water table	↑	Low
Organic matter addition	↑	High
Fertilizer N application	↓	Low
Increasing soil alkalinity	↓	High
Increasing soil salinity	↓	High
Soil wetness	↑	High
Alternate drying and wetting	↑	High
Conventional tillage	↑	High
Conservation tillage	↓	Low
Elevated CO_2	↑	High
Elevated temperature	↑	High

4.3.1.13 Changes in Atmospheric Composition

Rising levels of atmospheric CO_2 are expected to stimulate plant growth and soil C input but may also alter microbial respiration and organic matter decomposition process for the soils under both C_3 and C_4 crop plant (Mosier et al. 2002). The soil C accumulation potential is expected to be depressed due to increase in the soil C turnover rate with faster decomposition process under elevated CO_2 environment with no limitation in soil water or N availability (van Groenigen et al. 2014). That results in higher soil CO_2 fluxes under elevated CO_2 environment (Abbasi and Müller 2011).

Factors and their most likely effect on CO_2 emission with confidence level are tabulated in Table 4.5.

4.3.2 Methane Emission

All of the mineral soils are small sinks for atmospheric CH_4, whereas most of the peat soils emit CH_4. Net CH_4 emission from flooded fields to the atmosphere is the balance between CH_4 production in soils and its oxidation carried rice by archaea and methanogenic and methanotrophic bacteria in soils (Le Mer and Roger 2001). CH_4 emission from the rice fields is estimated to be globally 37 Tg year^{-1}. Around 70–80% of the total annual global emission of methane is biogenic in origin (IPCC 2007a, b). Microbial degradation of soil organic substances under anaerobic conditions generates CH_4 in soils, at very low redox potential. Such low redox condition prevails in natural wetlands and flooded rice fields under prolonged waterlogging, as well as in lake sediments (Bhaduri et al. 2017). The CH_4 formed in flooded soils and sediments often moves toward the surface and is emitted into the atmosphere by means of three different processes:

- Diffusion (often oxidized, common in submerged paddy, Krüger et al. 2002)
- Ebullition process (without oxidation, Conrad 1989)
- Transport of CH_4 (via aerenchyma cells of vascular plants, Lloyd et al. 1998)

The average lifetime of CH_4 in the atmosphere is about 10 years. UV-created hydroxyl radicals (OH^-) destroy about 90% of the atmospheric CH_4, while 5–10% diffuse from the atmosphere into aerobic top soils and get oxidized by different soil microbes (Prather et al. 1995). The major sources of CH_4 in our atmosphere include the digestive system of ruminant animal population (about 15% of the calculated annual global CH_4 emission), wetland rice agriculture (20%), gas loss during coal mining and oil production (14%), biomass burning (10%), and natural wetlands (24%) (Whalen 2005). In India, rice is cultivated as irrigated, rainfed, deepwater, or upland. Only 15% of the cultivated area is under upland condition, while most of the rice cultivation is under wetlands (irrigated, rainfed, and deepwater). Rice culture under wetlands has been identified as one of the major sources of global CH_4 emission (~40% of total CH_4 emissions, Prather et al. 1995). Around 80% of CH_4 produced in the agricultural soil are converted to CO_2 in the oxidized zone in the surface soil of rice fields where CH_4 reaches by diffusion (Conrad and Rothfuss 1991). The major biological sink of atmospheric CH_4 is oxidation by methanotrophic bacteria in aerobic soils (Xu et al. 2003). In well-drained soils, methanotrophic bacteria oxidize only 10% of atmospheric CH_4 of the total global sink (Topp and Pattey 1997). It is projected that to meet the regular food demand of the ever-increasing global population, increased wetland rice culture is essential with rapid expansion and intensification of rice cultivation in the coming decades. As a consequence, a significant rise in CH_4 fluxes to the atmosphere is expected from the wetland rice fields, considering the current technological progress as constant one (Singh et al. 1999; Anand et al. 2005). The major factors influencing the magnitude and variability of CH_4 emission from soil have already been discussed in chapter 3 entitled “Methane Emission from Wetland Rice Agriculture: Biogeochemistry and Environmental Controls in the Projected Changing Environment.” In brief, the factors and their most likely effect on CO_2 emission with confidence level are shown in Table 4.6.

4.3.3 Nitrous Oxide Emission

Among all the anthropogenic GHGs, N_2O is one of the most important long-lived tracers contributing to the changes to the global N cycle and global warming and plays a crucial role in stratospheric ozone (O_3) depletion. Transportation into the stratosphere is the most significant means for the removal of atmospheric N_2O, where it is photolytically oxidized to NO which reacts with stratospheric ozone and absorbs harmful solar ultraviolet radiation. The global estimate recalls that doubling the atmospheric N_2O concentration in the atmosphere may result in about 10% decrease in the ozone layer with 20% increase in the ultraviolet radiation reaching the Earth’s surface (Crutzen and Ehhalt 1977). Nitric oxide (NO) is involved in the

Table 4.6 Factors and their most likely effect on CH_4 emission with confidence level

Factors	Most likely effect on CH_4 emission	Confidence level
Continuous flooding in rice fields	↑	High
Intermittent flooding	↓	High
Increasing clay % in soil	↑	Low
Increasing water table depth	↑	High
Organic matter addition	↑	High
Fertilizer N application	↓	High
Hybrid rice/early-maturing rice	↓	Low
Increasing soil salinity	↓	High
Conservation tillage	↓	Low
Elevated atmospheric CO_2	↑	High
Elevated temperature (soil and air)	↑	High
Elevated atmospheric O_3	↓	High

complex photochemical reactions, which is a precursor of nitrogen dioxide and nitric acid that leads to environmental acidification (Ravishankara et al. 2009). It has two opposing indirect greenhouse effects through tropospheric ozone enhancements and methane (CH_4) reductions (Pathak et al. 2016). The agriculture sector (soil and livestock) is the major source of N_2O, contributing about 42% of anthropogenic N_2O emissions worldwide (IPCC 2007a, b). The atmospheric N_2O concentration has reached 324 ppbv as compared to the preindustrial level of 270 ppbv (WMO 2011). Due to the long atmospheric lifetime and higher warming potential of this GHG, greater attention has to be paid on the mechanistic evaluation of the production and emission of N_2O and other oxidized forms of gaseous nitrogen (NO_x).

Unlike methane emission which is mostly confined for the flooded rice fields and wetland agriculture, the problem of N_2O emission is widespread that cover the production practices of almost all arable crops in addition to the previously mentioned one. For any successful crop production, N fertilization is necessary to enhance our crop productivity. N application to soils as chemical or organic fertilizers provides the necessary substrates for growing the microbes involved in the biochemical processes of nitrification (aerobic) and denitrification (anaerobic) that further promotes the anthropogenic N_2O emission from soil environment. N_2O in the soil environment is mostly produced either from the natural microbial nitrification or denitrification processes by denitrifiers (Hayatsu et al. 2008) along with the non-biochemical process of chemo-denitrification (mostly under acidic soil conditions) and decomposition of hydroxylamine (Venterea et al. 2005). Microbial nitrification and denitrification in managed and natural soils contribute approximately 70% of global N_2O emissions (Butterbach-Bahl et al. 2013).

Under low oxygen availability, NH_3 oxidation pathways and nitrifier denitrification are also accounted as the significant sources of N_2O (Kool et al. 2010). N_2O formed inside the soil is released into the atmosphere by the processes of diffusion (in aerobic soils), ebullition (in waterlogged soils), and vascular transport (bundle sheath tissue assembly). The uptakes of N_2O by the soils with low N in dry regions exploit N_2O as N substrate in the absence of NO_2^- and NO_3^- to sustain soil microbial denitrifiers (Rosenkranz et al. 2006). Alternatively, the nitrogenase enzyme involved in biological N_2 fixation in the surface soil can use N_2O as a substrate (Jensen and Burris 1986). N_2O emission from organically managed soils is influenced by soil characteristics, and for the nonorganically managed soils, it is often dependent on total N inputs (Skinner et al. 2014). The magnitude and variability of N_2O production and emission from soil depends upon a wide range of weather, soil, management, and plant-related factors as described below.

4.3.3.1 Weather Factors

Warmer air temperature and high wind speed accelerate the soil N_2O emission (Ding et al. 2007). High wind speed maintains N_2O concentration gradient between soil and the atmosphere if continuous N_2O reduction is occurring in soil. Low rainfall promotes soil dryness ($< 25\%$ water-filled pores) that is not conducive for fast nitrification along with high O_2 concentration, which is toxic to denitrifiers. Thus, the soil N_2O production and emission process is inhibited (Tellez-Rio et al. 2015). However, sufficient rainfall promotes soil moisture as well as enhanced N_2O emission under anaerobic soil environment (Zhang and Han 2008). N_2O flux increases substantially after sufficient rainfall due to increased nitrifying and denitrifying activity within hours of wetting a soil (Majumdar et al. 2002).

Freeze-thaw cycles also promote N_2O production and emission under temperate climate condition (Sehy et al. 2003). Under sufficient N supply, the N_2O emission potential of clay soils with high NH_4^+ fixation capacity increases during freezing-thawing periods (Singurindy et al. 2009), whereas heavy rainfall events often enhance NO_3^- leaching that may inhibit N_2O emission (Livesley et al. 2011). In certain circumstance, summer dryness often enhances the soil nitrifying activity as a source of soil N_2O emissions. The N_2O emissions during nitrification may not be constant, but depend on season-specific soil temperatures and land management practices during the post-harvesting period (Henault et al. 1998).

4.3.3.2 Soil pH

Soil pH has direct control over denitrification, mineralization, and immobilization, therefore controlling the N_2O production and uptake within the soil environment. Denitrification occurs for a much range of soil pH that varies from 3.9 to 9.0 (Włodarczyk 2000). But the nitrification process is mostly confined for relatively narrower range soil pH from 3.8 to 8.5 (Subbarao et al. 2006). *Nitrosomonas* requires an optimal pH between approximately 7.0 and 8.0, and the optimum pH range for *Nitrobacter* varies from 7.5 to 8.0. Nitrification can occur in acid soils with a pH as low as 3.8, though at a much slower rate (Tisdale and Nelson 1970). Denitrification rates in acidic soil pH are slower than under slightly alkaline conditions (Ussiri and Lal 2013). However, the optimum pH for both nitrification and denitrification varies between the soil pH range of about 7.0–8.0 (Włodarczyk 2000; Van den Heuvel et al. 2011). Under adequate supply of NO_3^- in the soil solution, the overall rates of both denitrification and nitrification often decrease with increasing soil acidity (Włodarczyk 2000; Dalal et al. 2003). N_2O reductase activity is more sensitive to the proton activity than NO_3^- reductase, i.e., the reduction of N_2O to N_2 is more sensitive to acidic conditions than the reduction of NO_3^- to N_2O (Lesschen et al. 2011). The larger share of N_2O fraction in the total N products liberated from the denitrification process in acid soils may be resulted from the decreased rate of N_2O reduction at low soil pH. This allows the net N_2O built within the soil environment and promotes soil N_2O emission, with its peak at pH 5.0 (Van den Heuvel et al. 2011). As the soil pH increases, the net N_2 production rates often dominates over the net NO_3 reduction rate, and that leads to the denitrification products to be more, or completely, toward N_2 production with significant reduction in N_2O/N_2 ratio (Focht and Verstraete 1977).

4.3.3.3 Soil Redox Potential (Eh)

Soil N_2O emission is favored for a wider range of soil redox potential from +500 to −250 mV. Denitrification process dominates for soil redox levels <+200 mV. Significant N_2O emission only occurs when the soil redox potential reaches > +200 mV. The peculiarity lies with two maxima for N_2O evolution curve with changes in the soil redox potential. Nitrification peak occurs at +400 mV and at 0 mV for denitrification process (Masscheleyn et al. 1993; Hou et al. 1998). With increasing degree of reduction in the soil environment, the net amount of liberated N gases also increases. But, the percentage of N_2O formation in the denitrification products (i.e., the total amount of N_2O and N_2 production) decreases with increasing anoxic conditions (Weier et al. 1993; Masscheleyn et al. 1993).

4.3.3.4 Soil Texture

Soil texture and particle size distribution affect N_2O emission by influencing soil aeration and moisture status. Heavy-textured poorly drained soils emit more N_2O than light-textured well-drained soils (Laegried and Aastveit 2002). Essentially, the entrapment of N_2O generated in the heavy clay soils also provides a greater scope to denitrify into elemental nitrogen gas under anaerobic conditions (Velthof and Oenema 1995). Compacted soil with higher content of clay-associated aggregates promotes denitrification and emits higher N_2O than sandy soils (van Groenigen et al. 2004; Singurindy et al. 2009).

4.3.3.5 Soil Structure

Soil structure interacts with the N_2O emission process from soil. Increased aggregate stability, reduced soil bulk density, and greater air-filled porosity often depressed the N_2O emissions (Berglund and Berglund 2011). In the poorly aerated compact soils with sufficiently available moisture, N_2O emissions is triggered irrespective of NO_3^- concentrations in soil solution, due to enhanced anaerobic crop residue decomposition (Chirinda et al. 2010).

4.3.3.6 Soil Chemical Condition

Soil nitrate (NO_3^-) concentration has direct influence on the N_2O emission process from soil environment. Under anaerobic conditions, NO_3^- is reduced to NO_2, N_2O, and N_2. A lower NO_3^- concentration in soil solution and NO_3^-leaching from the top soil to the subsoil inhibits the formation of N_2O via denitrification (Ma et al. 2010). In the absence of NO_3^- accumulation, denitrification is the most likely source of N_2O. In general, the susceptibility of soil for emission loss of N_2O increased with increasing availability of NO_3^- in the soil. The strong inverse relationship between soil N_2O effluxes and NO_3^- leaching losses follows exponential decaying function (Zhou et al. 2013). Soils with small N_2O emission losses generally have a small soil inorganic N pool dominated by NH_4^+ (Davidson and Verchot 2000). In aquatic ecosystems NO_3^- may leached down into groundwater or surface waters (via agricultural runoff) and gets denitrified into N_2O flux (Groffman et al. 2002). Under most circumstances, the presence of NO_3^- inhibits the rate of N_2O reduction to N_2, resulting in a higher N_2O/N_2 ratio at similar moisture and oxygen contents (Dalal et al. 2003).

4.3.3.7 Soil Temperature

N_2O emission generally increases with soil temperature from 5 to 40 °C due to rise in the rate of nitrification, denitrification, and diffusion processes (Pereira et al. 2013). Temperatures lower than 5 °C reduce soil microbial activity and consequently reduce emissions (Singurindy et al. 2009). Increase in soil temperature (at least up to 37 °C) enhances microbial activity as well as soil respiration that leads to a depletion of soil O_2 and enhanced diffusion and within the soil medium under optimum moisture availability. Thus the denitrification process is promoted and the N_2O emission from soil is increased (Dalal et al. 2003; Butterbach-Bahl et al. 2013). The solubility of N_2O in soil water reduces and that further promotes N_2O emission (Majumdar 2003). Above 37 °C, the N_2O/N_2 ratio in denitrification increases with decrease in soil temperature (Maag and Vinther 1996). At higher temperatures (>50 °C) chemo-denitrification of NO_2^- dominates due to the increased activity of thermophilic nitrate respirers (Dalal et al. 2003). Annual variation in environmental temperature regime also influences soil microbial activity. But on annual basis the effect is almost negligible. In general, for the soil fauna under colder ecosystems, peak N_2O emission occurs during the warmer periods. In contrast, under warmer climates, the biological activity of the soil fauna reaches at peak during the wetter periods, therefore the higher N_2O emission from soil (Lesschen et al. 2011).

4.3.3.8 Soil Moisture and Aeration Status

The supplementary relationship between the soil moisture and soil aeration has the direct control on the N_2O emission dynamics from soil environment. The soil water-filled pore spaces (WFPS) strongly influence the N_2O production, likely via manipulating the oxygen availability within soil environment. Under unsaturated conditions, ~60% of N_2O came from nitrification, while denitrification contributed ~85–90% under saturated conditions (Mathieu et al. 2006). Conditions of WFPS have an exponential effect on the denitrifying activity of soils (Henault et al. 1998). The WFPS value of well-aerated soils ranges between 40 and 60%. The low N_2O production rate from nitrification at <40% WFPS increases rapidly with increasing moisture content (up to 55–65% WFPS). Above 60–70% WFPS, an increase in water content often hinders aeration (limits O_2 diffusion), promotes denitrification, and releases both N_2O and N_2. External supply of elemental O_2 inhibits N_2O reductase activity (Firestone et al. 1980). At high moisture (>80–90% WFPS), reduced oxygenation favors gaseous N loss denitrification. Under anaerobic environment, where the N substrate supply is non-limiting, the activity of denitrifying enzymes can vary from soil to soil. The reduction of N_2O to N_2 occurs in air-dry soils (1–2% soil moisture) with 0.03–21% initial O_2 concentrations (Singurindy et al. 2009). But the N_2O/N_2 ratio decreases as the soil water content exceeds 75% WFPS (Weier et al. 1993; Dalal et al. 2003). Well-drained sandy loam soil with low soil moisture (25–50% WFPS) under rainy conditions is often conducive to persistent net N_2O uptake from the atmosphere (Wu et al. 2013).

N_2O concentrations in the surface soil (up to 30 cm) increase with the increase in the soil moisture (Nosalewicz et al. 2013). High soil moisture content also strongly decreases gas diffusion through soil and supports denitrification process under anoxic environment, therefore increasing N_2O concentrations in soil environment (Singurindy et al. 2009). Even under well-aerated condition (60–70% WFPS), denitrification losses occur due to the presence of anaerobic microsites in soil aggregates (Müller et al. 2004). Decreasing soil aeration (by increasing the WFPS %) may increase the cumulative denitrification as well as cumulative N_2O emissions. The soil N_2O uptake often increases with decreasing WFPS. Rewetting dry soil promotes denitrification and often generates short-term N_2O pulses with variable N_2O/N_2 ratios (Rusera et al. 2006). Alternate wet and dry cycles stimulate N mineralization from organic matter, promote NO_3^- accumulation during the dry period, and increase N_2O production during the wet period as long as the soil does not get waterlogged (Dalal et al. 2003).

4.3.3.9 Soil Organic Matter

Peat soils may have higher N_2O emissions than sand and clay soils due to their higher denitrification potential and higher groundwater level (excessive wet conditions) (Velthof and Oenema 1995). In the soils rich in organic matter, denitrification often dominates over the nitrification activity mostly due to more substrate availability under anoxic environment and the sensitivity of nitrifying bacteria to the humic acids as well as low pH (De Boer and Kowalchuk 2001). Denitrifiers often use organic C compounds as electron donors. Therefore, denitrification is dependent on the availability of carbon and mineral nitrogen (preferably NO_3^-). Generally, organic peatland soil produces and emits more N_2O than the mineral agricultural soils by a factor varying from 2 to 10 (Odlare et al. 2012). Low pH of organic soils further facilitates the N_2O emission. High concentration of NO_3^- and organic material promotes the nitrification and denitrification processes, respectively, and increases the net N_2O emission from organic matter-rich soils. The ratio of N_2O emission factor varies as follows: sand: clay: peat = 1 (reference):1.5:2 (Lesschen et al. 2011).

4.3.3.10 Water Table Depth

Higher soil water tables often inhibit N_2O effluxes (Yang et al. 2013). Lowering the water table only increases emission rates if new layers with easily decomposable material or low C/N ratios are exposed (Berglund and Berglund 2011). More oxygenated soil under lower soil water table promotes the N_2O emission to the atmosphere. Excessive soil wetness may reduce the N_2O produced by denitrification into N_2 and thus reduce the emission even under high water table (Krausea et al. 2013).

4.3.3.11 Soil Salinity

High salinity often inhibits both nitrification and denitrification (Inubushi et al. 1999). The salt susceptibility of N_2O reductase (EC > 56 dS m^{-1}) often results in N_2O accumulation from denitrification under saline soil conditions (Menyailo et al. 1997). N_2O production from nitrification is promoted by increased salt concentration in the soil solution (Low et al. 1997). In addition, increasing soil salinity also ensures ample supply of NO_3^-, the electron acceptor for denitrifiers. The activity of NO_2^- reductase decreases with increased soil EC. Therefore, increasing soil salinity increases cumulative N_2O losses from anaerobic soils as well as the N_2O/N_2 ratios by increasing N_2O emission with subsequent reduction in N_2 emission (Reddy and Crohn 2014).

4.3.3.12 Nature of Added Organic Manure

Nature of organic manure often determines the magnitude of emitted N_2O. Organic matter provides the sources of carbon and energy for heterotrophic denitrifying organisms. Pig slurry emits more N_2O as compared to cattle slurry due to higher proportion of ammonium present in total N content of the pig slurries (Chadwick et al. 2000). Application of easily degradable C with manures increases potential denitrification and thereby the risk of greater N_2O production and emission from soil (Lesschen et al. 2011). But the N_2O/N_2 ratio of denitrification products decreases with increasing available C supply (Weier et al. 1993). In addition, the population of denitrifiers is often determined by the amount of different volatile fatty acids present in different animal manures as effective C sources for denitrification. Solid manure application emits less the slurry application. The magnitude of N_2O emission factor from different organic manures varies in the following order: pig slurry > cattle slurry > poultry manure (at about ~ 3:2:1 ratio) (Chadwick et al. 2000; Velthof et al. 2003; Lesschen et al. 2011). The productions of N_2O often ranged from 44 to 404 mg N kg^{-1} dependent on the kind of organic material, added to soil (Yang et al. 2002). However, the N_2O emission factor of different animal manures is considered to be the function of land-use dynamics (discussed later).

4.3.3.13 Earthworm Activity

Earthworms may contribute ~ 33% of the total emissions of N_2O from soil (Matthies et al. 1999). The gut-associated denitrifying bacteria of earthworm are responsible for N_2O emissions (Drake and Horn 2006). Earthworm activity may increase the soil N_2O emissions from crop residues by 18 times (Rizhiya et al. 2007). However, in well-aerated soil, sufficient supply of NO_3^- may enhance nitrification by the bacterial community present in the earthworm gut (Contreras-Ramos et al. 2009).

4.3.3.14 Land Use

Grassland soils experienced no-tillage and continuous supply of fresh organic matter via root exudates and other organic matter addition. Grassland soil have greater potential denitrification rate than arable land due to their greater C availability (Bijay-Singh et al. 1988). Therefore, addition of manure has less impact on N_2O emission from grassland as compare to arable land (Velthof et al. 1997). In addition, there is a lag phase between grassland and arable crops, for the utilization of N applied through manure material. A major fraction of applied N is utilized immediately after application, either by immobilization or crop uptake by the extensive rooting system of the grass species. Thus the scope of nitrification process of added fertilizer N is much limited for grassland soils. For arable field crops, manure applied before sowing operation is utilized by the crop after a considerable period of time, i.e., during crop establishment. This enhances the scope of nitrification of applied fertilizer N material. As a result, the N_2O emission factor from manure is substantially high for the soils under arable crops (1.5 times) than grassland soils. For fertilizer N material, the mechanism slightly differs. More reduced condition prevails in the organic matter-rich grassland soils that facilitate the N_2O emission more readily than arable croplands. Thus the N_2O emission factor is set at, respectively, 0.5 and 0.8 times of grassland soils for nitrate and ammonium-containing fertilizer material, respectively (Lesschen et al. 2011). During the conversion of grasslands to cropland, mineral N liberated by mineralization of soil organic matter and plant remains can be regarded as a comparable potential source of N_2O emission (Lobe et al. 2001).

4.3.3.15 Fertilizer N Application

External application of mineral fertilizer (N) is the most significant anthropogenic source of N_2O emission in agriculture. The risk of N_2O emissions increases, whenever the amount of applied N is above the crop requirement or available N exceeds crop uptake with better availability of soil moisture (Oenema et al. 2005). Under high soil moisture condition (WFPS value of 70% or more), N fertilization often increases N_2O emission considerably (Rusera et al. 2006). Fertilizer N addition increased soil N_2O emissions (Kim et al. 2012) due to increased soil N availability (in forms of NO_3^-) for microbial nitrification and denitrification (Wrage et al. 2001). Prolonged waterlogging may impede the N_2O diffusion from well below the soil surface to atmosphere and further reduced to N_2 by the process of anaerobic denitrification via increased N_2O reductase activity (Krausea et al. 2013). Application of urea- or NH_4^+-containing or NH_4^+-forming fertilizers in aerobic soils in upland crops (Velthof et al. 2003) and NO_3^--based fertilizers in low land crops emits more N_2O especially during wet conditions (Pathak and Nedwell 2001). In submerged paddy soils, the oxidizing and reducing layers are developed in the cultivated layer simultaneously. Application of NH_4^+-N-containing fertilizer promotes nitrification process in the oxidized layer, at the water-soil interface, forming NO_3^- that further moves downward to the underground saturated layer (Chatterjee et al. 2018b). In that reduced zone, NO_3^- gets denitrified to produce N_2O and emits into the atmosphere along with evaporative flux (Xing et al. 2009).

When synthetic mineral N fertilizers are added to the soil in combination with organic crop residues, soil N_2O emissions are depressed as compared to sole synthetic N fertilizers application. The effect of slower decomposition rates of the added straw materials (higher C/N ratio) dominates over the fertilizer N addition effect and promotes the immobilization of plant-available form of N (NO_3^-) that ultimately inhibits the N_2O release from soil (Yao et al. 2013). However, the application of readily decomposable organic manures in arable land often accelerates soil N_2O emissions than synthetic mineral fertilizer application (van Groenigen et al. 2004).

4.3.3.16 Crop Residue Management

Addition of crop residue to the mineral soils is often aimed to manipulate the organic matter content of the soil. Crop residue additions are often negatively correlated with the C/N ratio of the incorporated residues (Millar et al. 2004; Toma and Hatano 2007). Incorporation of N-rich crop residue (low C/N ratio) can increase N_2O emissions in soil (Baggs et al. 2000; Millar and Baggs 2005). But it is the land-use type factor that determines the nature of interaction between crop residue incorporation and N_2O emissions. Residue applied for fallow land and upland promotes N_2O emission from soil, whereas N_2O emission is suppressed in submerged paddy (Shan and Yan 2013). When residues are applied as straw mulch for fallow land, they conserved soil moisture and supplied sufficient organic substrates for denitrification, thus resulting in higher N_2O emission (Jacinthe and Lal 2003). For upland soils, crop residue application often resulted in higher soil temperature and moisture content, which stimulated the activity of nitrifier and denitrifiers, leading to more anaerobic conditions. Therefore, the denitrification process is promoted with enhancing production and subsequent emission of N_2O from soil environment (Ma et al. 2010; Shan and Yan 2013).

In contrast, addition of crop residues (preferably cereal straw materials; high C/N ratio) in lowland paddy fields inhibits the N_2O release (Shan and Yan 2013), indicating net immobilization of plant-available N that results in reduced N availability with increasing C/N ratio. N_2O production is suppressed due to the lower availability of nitrogen substrates (Yao et al. 2013). The residual inhibitory effect on N_2O emissions remains for another crop season. It is often argued that the high lignin content of the crop residues determines the soil N_2O emission rate rather than the C/N ratio of the crop residue (Muhammad et al. 2011).

4.3.3.17 Crop Rotation

Crop rotation practices (i.e., N_2 fixing green manure and catch crop) often reduce soil N availability (via immobilization) that constrains soil N_2O emissions (Askegaard et al. 2005). Inclusion of legumes in cereal-based cropping system can reduce the N_2O emission by curtailing the fertilizer N application rates (Delgado et al. 2007) and promoting the additional source of biologically fixed N (less available for nitrification and denitrification process) (Parkin and Kaspar 2006). Catch crops control NO_3^-leaching (restricted drainage losses) and extract the unutilized plant-available N (NO_3^-) forms after harvesting of main crop. Thus the excess soil NO_3^- is reduced as well as the N_2O emissions from the soil environment (Feyereisen et al. 2006). But the suppressing effect of legume inclusion on soil N_2O emissions may be minimized if the litter decomposition rate is higher under restricted soil aeration (Chirinda et al. 2010).

4.3.3.18 Tillage

Any type of soil disturbance either via tillage or intercultural operations generally promotes soil aeration. The external oxygen entry into the soil environment modifies transport processes which can give the generated N_2O a better chance of escaping before being denitrified to N_2 and promotes the N_2O release from soil (Majumdar 2003). But different tillage systems (conventional, conservation/minimum, and no-tillage) have no significant effect on total soil N_2O emissions over the total crop growth period due to their least influence on the size of denitrifier populations and their denitrification capacity (Tellez-Rio et al. 2015). The beneficial effect of tillage is attributed to changes in soil structure, which in turn affects the soil aeration (Plaza-Bonilla et al. 2013). In conventionally tilled soil, the disturbance during crop harvest followed by turnover of crop residues through subsequent tillage operation promotes the mineralization of crop residues and accumulation of NO_3^-resulting to more N_2O emissions from the soil to atmosphere (Millar et al. 2004). Lower N_2O production from the no-tillage soil system is attributed to lower volume of anaerobic microsites and reduced diffusion coefficient along with more N_2O consumption in the upper soil layer in long-term no-tillage soil system, as compared to the soils under conventional and minimum tillage system (van Kessel et al. 2013). In general, long-term adaptation of conservation/no-tillage practice may give the benefit of reduced N_2O emission in the long run due to increase in SOM storage, improved soil structure, enhanced aeration, and reduced soil bulk density. No-tillage promotes more anoxic reduced sites in the poorly aerated soils (due to restrict drainage) with high clay content under wet and humid condition that may alter the microbial population and increase N_2O emissions due to enhanced denitrification (Yao et al. 2013; Tellez-Rio et al. 2015).

4.3.3.19 Changes in Atmospheric Composition

Under elevated CO_2, sufficient supply of available N in the soil environment stimulates canopy photosynthesis, and photosynthate supply to roots stimulates root exudation that is expected to promote denitrification in flooded rice soils (Bhattacharyya et al. 2013a, b). In addition, increases in soil water content due to dramatic reduction in canopy transpiration and labile soil C pools may further stimulate the N_2O efflux under elevated CO_2 (Arnone and Bohlen 1998). However, the effect of increasing substrate availability to promote denitrification is often limited by lower N availability (Carter et al. 2011; Pereira et al. 2013). The cumulative seasonal N_2O emissions from rice decrease in response to elevated atmospheric

Table 4.7 Factors and their most likely effect on N_2O emission with confidence level

Factors	Most likely effect on N_2O emission	Confidence level
Continuous flooding	↓	Low
Alternate drying and wetting	↑	High
High water table	↓	High
Organic matter addition	↑	Low
Fertilizer N application	↑	High
Crop residue management	↓	Low
Increasing soil salinity	↑	High
Increasing soil acidity	↓	High
Catch crops/crop rotation with legumes	↓	Low
Conventional tillage	↑	High
Conservation tillage	↓	Low
Elevated CO_2	↑	High
Elevated temperature	↑	High
Elevated O_3	↓	High

O_3 concentration (Bhatia et al. 2011), due to the decreased activity of nitrifying and denitrifying bacteria with reduced available N content in soil under elevated ozone environment (Kou et al. 2014). Factors and their most likely effect on N_2O emission with confidence level are tabulated in Table 4.7.

4.4 Impact of the Projected Changing Environment on Nutrient Transformation in Soil and Its Plant Availability Dynamics

The changing environmental variables will most likely impact on nutrient transformation in soil and also alter its plant availability dynamics. The nutrients like C and N are controlled by biological cycles and may show a different reaction to the changing climatic variables than the elements with cycles controlled both by geological and biological processes, such as P, S, and K, or elements with predominantly geologically controlled cycles, such as K, Ca, Mg, S, or micronutrients (Lukac et al. 2010). In this section we will confer how the climate change alters the processes of the cycling and availability of these nutrients.

4.4.1 Carbon

The decomposition of resistant soil organic matter is more temperature-sensitive than labile organic matter (Leifeld and Fuhrer 2005). However, a report concludes, both in 2-year and 10-year experimental warming, a little effect on the MBC, MBN, and MBP and the contribution of microbial biomass to soil nutrient pools (Wang et al. 2014).

Among the different carbon pools, total organic carbon (TOC) in root exudates increases by 29% under elevated CO_2 than ambient (Bhattacharyyaa et al. 2014). Again, elevated CO_2 increases plant photosynthesis and biomass accumulation and thus increases the rhizodeposition (Kim et al. 2001), which is the key contributor to belowground C allocation and enriches soil labile C pools (Bhattacharyya et al. 2013b). Among the different fractions of soil organic matter in soils, microbial biomass carbon (MBC) is the most labile fraction and plays a pivotal role in soil nutrient cycling (Bhattacharyya et al. 2013a). All the labile carbon pools (like MBC) are increased under elevated CO_2 (Bhattacharyya et al. 2013a). In general, MBC in soil grown with rice doubled at elevated CO_2 compared to ambient (both in open field and in OTC) (Manna et al. 2013).

The conjoint effect of both CO_2 and elevated temperature significantly increases the soil labile carbon, MBC, and β-glucosidase activity which is a carbon-transforming enzyme in soil (Bhattacharyya et al. 2013b). Under elevated CO_2 and temperature, the water-soluble carbohydrate carbon increases due to enhanced microbial activities (Bhattacharyya et al. 2013b). This parameter mostly represents the free sugars and microbial polysaccharides present in the soil (Manna et al. 2005).

4.4.2 Nitrogen

Increase in temperature is likely to impact N availability in soil through stimulation in decomposition and mineralization of SOM. However, the effect of elevated temperature on nitrogen depends upon the ecosystem and season (Lukac et al. 2010). The enzymes controlling the N cycle will be more active under the elevated temperature. The highest increase in enzyme activities is observed during the winter when temperature is lesser than other season or in the spring because of the maximum root and microbial activity (Beier et al. 2008). The NH_4 content decreases in spring in concomitance with the increase in N uptake by plants, whereas NO_3 content is increased at the same time, due to an increase in nitrification activity (Beier et al. 2008). Studies shows the soil warming can increase net N mineralization and nitrogen loss through nitrate leaching (Pendall et al. 2004). On the contrary, nitrogen mineralization was reported to be unresponsive to the temperature but mostly affected by alteration in soil moisture (Beier et al. 2008). The enzyme activities involved in N cycling increased in response to elevated temperature have also been reported in the presence of sufficient moisture (Sardans et al. 2008).

Due to the strong link between C and N cycles, N is the most limiting element likely to hinder plant growth in a future high-CO_2 world (Reich et al. 2006). Under the increasing level of elevated atmospheric CO_2, photosynthetic C assimilation is expected to be stimulated (especially in C_3 crop species) with increased belowground C allocation through root exudation and turnover, which probably lead to the modification in soil microbial activity (Rillig et al. 2001). Enhancing input of C under elevated CO_2 was reported to stimulate either microbial N immobilization

(Zak et al. 2000) or mineralization due to priming effect (Blagodatskaya and Kuzyakov 2008), depending on the limitation of C or N in microbial communities and on the C/N ratio of the decomposing substrate (Hodge et al. 2000). If there is more immobilization of soil N, then the plant's ability to respond to the increase in the atmospheric CO_2 concentration will be reduced, ultimately resulting in a decrease in yield of the crops (Hu et al. 2001). The leaf N content per unit leaf area will decline under elevated CO_2 (Ellsworth et al. 2004). In perennial trees, the process of N retranslocation from leaves to woody parts before their abscission will be slightly increased by elevated CO_2; thus more N will be immobilized in woody tissues (Calfapietra et al. 2007). Immobilization of N occurs not only in plant parts but also in soil too. For instance, in inceptisols rice and wheat were grown at increased CO_2 concentration (550 ppm) as well as in ambient CO_2 condition (380 ppm). The microbial biomass carbon (MBC) was significantly higher under increased CO_2 than ambient, while NH_4^+-N and NO_3^--N were higher in the ambient plots due to N immobilization in both the crops. Soil organic carbon (SOC) did not show much change with high-CO_2 treatment (Chakrabarti et al. 2012).

4.4.3 Phosphorus

Soil temperature influences the supply and uptake of phosphorus (P) by plants; hence understanding its dynamics under climate change scenario is of utmost importance. Availability of soil phosphorus under 2 °C elevated temperature than ambient significantly decreased the soil available P content by 18.8% at jointing stage of wheat in China (Zhang et al. 2014). On the contrary, another report from the same country says the soil warming at 0.8–1.1 °C above the control in short-term (2 years) and long-term (10 years) experiments does not significantly affect soil pH; bulk density; total carbon, nitrogen, and phosphorus; organic carbon; available phosphorus; NO_3-N; microbial biomass C, N, and P; and cellulase, catalase, and phosphatase activities (Wang et al. 2014).

The effect of elevated CO_2 on P availability is likely to be indirectly related and mediated by the response of biological components of the soil ecosystem. Phosphorus availability is driven by the action of ectoenzymes produced by roots, mycorrhizal hyphae, and soil microorganisms (Read et al. 2004; Chatterjee et al. 2014, 2015). It is observed that production of such enzymes increases under elevated atmospheric CO_2 (Lagomarsino et al. 2008), which reflects an increase in demand for P by microorganism or plant or by both. Moreover, tree roots and mycorrhizas also contribute to mineral weathering and successive release of P (Dijkstra et al. 2003). Therefore, increases in belowground carbon availability under elevated CO_2 may lead to increased P mineralization and release of P from the soil mineral fraction. Due to widespread deficiency of available P in Indian soils, it is expected to become a critical nutrient to facilitate the crop responses toward the rising atmospheric CO_2 level (Kumar et al. 2011). Elevated CO_2 significantly increased soil available P content by 14.3% in the jointing stage of wheat in China (Zhang et al. 2014). In India, Bhattacharyyaa et al. (2014) show that available P under elevated CO_2 is significantly increased by 25.8, 23.3, and 28.7% over open-top chamber control in three consecutive *kharif* rice cultivations. Also, soil available P in three *kharif* seasons in elevated CO_2 has increased by 23% over ambient. The reason of such increase may be attributed to the increase in organic acid in root exudates by 41% in elevated CO_2 than ambient. They also show an increase in microbial biomass P and phosphatase activity in elevated CO_2 by 35.1 and 32%, respectively. The P uptake in shoot, root, and grain increases by 29, 28, and 22%, respectively, under elevated CO_2. Kumar et al. (2012) report an increase in total P uptake under elevated CO_2 (650 ppm) and a decrease under elevated temperature (+3 °C), with an overall increase of 17.4% under elevated CO_2 and temperature in *Typic* Haplustept of New Delhi under subtropical India.

4.4.4 Potassium, Secondary Nutrients, and Micronutrients

The effects of climatic variabilities on potassium, secondary nutrients, and micronutrients are not much studied. Nutrient availability in soil is based on the cation-exchange capacity (CEC), which may be strongly affected by elevated CO_2. An increase in base cation availability (Ca and Mg), along with an overall increase in CEC, was found under elevated CO_2 (Lukac et al. 2010). Under elevated CO_2, rates of K^+, Ca^{2+}, and Mg^{2+} uptake are increased (Delaire et al. 2005). Liu et al. (2007) reported a decrease in S and B concentrations, increase in K and P concentrations, and no effects on other elements (Mg, Ca, Mn,Cu, Zn) in aspen and birch leaf litter under elevated CO_2. At the same site, nutrient input of N, P, S, P, Ca, Mg, Cu, and Zn to soil through leaf litter decomposition under elevated CO_2 increased, but the return of Mn was reduced.

4.5 Impact of Environmental Modifications on Soil Biological Environment

Microorganisms play a significant role in the soil ecological processes. They are involved in global nutrient cycling, decomposition of plant and animal residues, and production and consumption of greenhouse gases, and thus they are very important in the context of climate change. The complexity of soil microbial communities and their association with their surroundings make it difficult to identify the feedback responses that soil microbes may have to global warming (Amendolara 2011–12). The effects of climate change are mainly visible on the macroscopic life, but the microbial world is also altered. Soil microorganisms are involved in the production and consumption of greenhouse gases, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Human activities such as waste disposal and agriculture stimulate the GHG production by soil microbes (Amendolara 2011–12). As concentrations of these GHGs are ever increasing due to anthropogenic emission, soil microbes may have differential feedback responses that may speed up or slow down the global warming, but the extent of these effects is a researchable issue till now. Understanding the role of soil microbes, as they have a definite role in both contribution and mitigation of GHGs, can help to determine whether they can be managed to curtail emissions. Microbial processes are often reliant on environmental factors like soil moisture, temperature, enzyme activity, and availability of essential nutrients, all of which are likely to be affected by climate change (IPCC 2007a, b; Bradford 2013; French et al. 2009). Hence understanding the effect of climatic variables (temperature, carbon dioxide, moisture, etc.) on soil microbial biodiversity (structure, function, and abundance) and soil enzymatic activities under the modified climatic situation may provide significant feedback effects of climate change and global warming.

4.5.1 Soil Microbial Biodiversity, Population, and Biomass

Biodiversity is defined as "the variability among living organisms from all sources including, inter alia, terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species (genetic diversity), between species (species diversity) and of ecosystems" (Heywood and Watson 1995; Mandal and Neenu 2012). The biological role of species or groups of species in an ecosystem is described by functional diversity. The soil contains a diversified group of macro- and microorganisms. Broadly, they are classified into two groups, viz., soil flora and soil fauna. Based on the body size, soil flora is again subdivided into microflora (e.g., bacteria, fungi, actinomycetes, and microalgae like blue green algae) and macroflora (e.g., roots of higher plants). Similarly, soil fauna is classified into microfauna (e.g., protozoa, nematodes), mesofauna (e.g., acari, springtails, and enchytraeids), and macrofauna (e.g., insects, earthworms) (Swift et al. 1979).

The diversity and composition of the aboveground plant community influences the soil microbial community through the supply, timing, and composition of residues and exudates (Bever et al. 2012; Kardol et al. 2007; Scherber et al. 2010). There are many reports showing the evidence that environmental modifications (increasing in temperature, elevated carbon dioxide, drought, excess moisture, etc.) significantly impact on the abundance, diversity, and activity of soil biota (de Vries and Bardgett 2014; Procter et al. 2014; Lipson et al. 2014).

4.5.1.1 Effect of Elevated Temperature

Increase in temperature may influence the ecosystem functioning by changing the physiology of the affected species, once it exceeds the physiological tolerance of species and/or disturbs their functional relationships with other species. Under such situations species may become extinct and thus the ecosystem's biodiversity may be reduced (Kappelle et al. 1999). Elevated temperature hastens up the microbial decomposition and soil respiration; thus it increases CO_2 emission and produces a positive feedback to global warming (Allison et al. 2010). Increased temperature generally increases the decomposition of organic matter (Wallenstein et al. 2012), and such effect is more on "recalcitrant" SOM than "labile" SOM (Bauer et al. 2008) because warming helps to rise above the critical activation energy (Ea) needed for decomposing the resistant compounds (Dungait et al. 2012). This may allow soil microorganisms to access older soil C stocks under climate warming and release more C into the atmosphere. Increased temperature may help to:

- Increase the microbial biomass initially as a direct response to the supplied heat but may decrease over time as microbial growth efficiency is altered (Schimel et al. 2007; Slaughter 2012). Increased catabolic response to sucrose and cellulose due to warming treatments is also observed (Slaughter 2012).
- Favor fungal and bacterial abundance (Castro et al. 2010; de Vries and Bardgett 2014). But, the bacterial abundance is more responsive to the interactive effect of CO_2 and temperature due to a lack of labile substrates under elevated temperature alone, which favors fungal over bacterial community members (Castro et al. 2010).
- Enhance population density of nematode in arctic soils but reduce the species number, richness, and diversity and maturity index (Ruess et al. 1999). Fungal feeders are more responsive to an increase in temperature than the bacterial feeders (Ruess et al. 1999).
- Increase most of the soil faunal groups (de Vries and Bardgett 2014). Developmental rate of collembolan, mesostigmatid, and oribatid mites is temperature-dependent. Fecundity and sex ratio in the populations of collembolans are altered (Lindberg 2003).
- Change the structure of the soil food web (de Vries and Bardgett 2014).

4.5.1.2 Effect of Increased CO_2

Impact of increasing atmospheric CO_2 is mainly because of the changes in the organic C dynamics due to alteration in plant photosynthesis. As the most of soil organisms are heterotrophic and dependent on the organic C input, the microbial activity will largely be influenced by changes in CO_2 concentration in the atmosphere (Drigo et al. 2008). Elevated atmospheric CO_2 influences on soil microorganism indirectly by increasing plant metabolism and root secretion of C_3 plants (Willey et al. 2009). These metabolites and secretions promote the mycorrhizae, bacteria, and fungi growth in the rhizosphere. Thus, the impact of elevated CO_2 on soil microbial population is characterized as follows:

- Increase in microbial biomass, species richness, and abundance of fungi (Procter et al. 2014; de Vries and Bardgett 2014; Lipson et al. 2014).
- Increase in abundance of certain bacterial phylogenetic groups like *Acidobacteria*, *Chloroflexi*, *Nitrospirae*, *Planctomycetes*, and *Proteobacteria* (Castro et al. 2010) and also an increase in bacterial biomass (Hu et al. 2001). Another report says under elevated CO_2, the bacterial biomass, richness, and community composition have been varied between ecosystems, resulting in no common trends, except a 3.5-fold decrease in the relative abundance of *Acidobacteria* group 1 bacteria (Dunbar et al. 2012).

- Shift in community composition of *Pseudomonas* spp. (Marilley et al. 1999) and *Rhizobium* species (Montealegre et al. 2000). The HCN-producing *Pseudomonas* strains are considered as potential inhibitors of root parasitic fungi. The proportion of HCN-producing *Pseudomonas* reduced when the plants were grown at elevated CO_2 (Tarnawski and Aragno 2006).
- Increase in mycorrhizal colonization due to increase in plant demand for nutrients, coupled with increased carbon assimilation rates (Johnson and Gehring 2007).
- Increase in the abundance and body size of most faunal groups (de Vries and Bardgett 2014).
- Shift in the nematode community structure, increasing the bacterivores and decreasing fungivores (Neher et al. 2004; Drigo et al. 2008).
- Increase in the activities of the grazers (like protozoa and microarthropods) of soil bacteria and fungi (Williams et al. 2000).
- Change in the structure of the soil food web (Phillips et al. 2006a, b; de Vries and Bardgett 2014).
- It does not predictably alter microbial biomass (Lipson et al. 2006; Zak et al. 2000).

4.5.1.3 Effect of Change in Soil Moisture Regime

Precipitations alter soil moisture regimes and regulate the decomposition during the period of moisture excess, i.e., anoxia, or moisture stress, i.e., drought. Less is known about the variable and complex soil microbial community response to alterations in precipitation or moisture than that of temperature or increased atmospheric CO_2 (Balser et al. 2010). Microbial communities are able to adapt to the inherent moisture regime of the soil and also respond to drying or wetting in different ways. This complexity of response does not allow to provide a generalized remark about the microbial response to soil moisture (Balser et al. 2010; Evans and Wallenstein 2012). Changes in soil moisture do not always lead to predictable or significant changes in bacterial and fungal abundance (Williams 2007). Nevertheless, a few examples are jotted down showing the effect of moisture regime:

- The ratio of precipitation and evaporation affects the soil microbial biomass (Insam 1990).
- Grassland ecosystems dominated by fungal-based soil food webs have shown resilience and adaptability to drought, compared to bacteria dominated wheat soils (de Vries et al. 2012).
- Microbial fatty acid abundance is affected by soil moisture (Bardgett et al. 1999).
- Precipitation influences the relative abundance of bacterial phyla. A shift in relative abundance of *Proteobacteria* and *Acidobacteria* is observed. The relative abundance of *Proteobacteria* is higher in the wet treatments, whereas *Acidobacteria* abundance is higher in dry treatments (Castro et al. 2010).
- Drought increases the abundance of fungi relative to bacteria (de Vries and Bardgett 2014).

- Drought decreases the biomass and abundance of most microbial and soil faunal groups (de Vries and Bardgett 2014).

4.5.1.4 Interaction of Temperature, Carbon Dioxide, and Soil Moisture Regime

Changes in climatic variables such as increased atmospheric CO_2, altered temperature, or precipitation regimes are unlikely to act individually, as often they will be varying simultaneously (Slaughter 2012). The interactive (e.g., additive, subtractive, or multiplicative) effects of these conditions are powerful drivers of soil microbial responses (Paul and Clark 1996; Slaughter 2012). Some examples of such interaction are as follows:

- Plentiful soil moisture in combination with increased temperature used to speed up the decomposition due to increased microbial activity and efficiency (Bontti et al. 2009). In case of limited soil moisture, elevated temperature is likely to inhibit microbial function (Bontti et al. 2009; Butenschoen et al. 2011).
- Interaction between soil moisture and elevated CO_2 is the main factor explaining variations in microbial community structure (Guenet et al. 2012).
- The effect of rise in temperature and frequency of precipitation in summer is statistically insignificant for most microfaunal groups, except amoebae. The seasonal increase in abundance of amoebae is reduced with combined effect of temperature and precipitation as compared to either of the treatments alone (Darby et al. 2011).
- A few studies show the effect of increased atmospheric CO_2, temperature, and precipitation together. A study by Castro et al. (2010) showed that the bacterial abundance increased in elevated temperature with elevated atmospheric CO_2, but decreased in in elevated temperature with ambient atmospheric CO_2. The relative abundance of certain bacterial groups responded strongly to the precipitation.

4.5.2 Soil Enzymatic Activity

Soil enzymatic activities explain the rate at which soil microbes obtain energy from organic and inorganic compounds in the environment since they use extracellular enzymes to catalyze metabolic reactions (Fuhrmann 2005). Extracellular enzymes are released outside the microbial cell to catalyze the reactions that decompose polymeric compounds which are too large to pass through the cellular membrane. Soil enzymes enhance the decomposition of soil organic substrates, release plant nutrients, and can determine whether soil organic carbon is sequestrated or depleted (Fansler et al. 2005). Extracellular enzymes like phosphatase and dehydrogenase also participate in the decomposition of SOM (Bell et al. 2010).

Production and activity of a specific enzyme mainly depend on the concentration of relevant compounds or substrates. The in situ enzyme activity is sensitive to temperature and moisture (Steinweg et al. 2012), but it is also controlled by quantity of substrate. Rates of production and turnover of soil enzyme are influenced by temperature and moisture and thus affected by change in climatic variables (Steinweg et al. 2013). Changes in the soil microclimate by the climatic variables affect the enzyme pool sizes. In response to increased activity of the existing enzyme pool, microbes may allocate less resources to enzyme production if microbial biomass remains unchanged (Allison and Vitousek 2005).

4.5.2.1 Effect of Elevated Temperature

- Increasing temperature is generally known to increase the enzyme activities (Koch et al. 2007).
- Long-term warming could induce changes in plant species composition, which can significantly affect soil microbial production of extracellular enzyme activity (Henry 2012).
- N-degrading enzymes have lower temperature sensitivities than C-degrading enzymes (Stone et al. 2012). Under increasing N limitation in soils at elevated temperature, spurring of microbes may occur to increase the production of N-degrading enzymes and decrease the production of C-degrading enzymes.
- The activities of enzymes like β-glucosidase, cellobiohydrolase, xylosidase, acid phosphomonoesterase, N-acetylglucosaminidase, and leucine aminopeptidase increase with increasing temperature at 0–5 cm soil depth. β-glucosidase and acid phosphomonoesterase show the highest activity under warmer climate (Steinweg et al. 2013).

4.5.2.2 Effect of Increased CO_2

- Soil alkaline phosphatase increased linearly with CO_2 in the sandy loam type of soil (Kelley et al. 2011; Fay et al. 2012).
- Elevated CO_2 increased acid phosphatase activity (Guenet et al. 2012).
- N-degrading enzyme activity increased with elevated CO_2 in the black clay (Kelley et al. 2011; Moore-Kucera et al. 2008; Brooks et al. 2011).
- Significant increase in invertase, xylanase, urease, protease, and alkaline phosphomonoesterase activities under elevated CO_2 (Drissner et al. 2007).

4.5.2.3 Effect of Change in Soil Moisture Regime

- Soil moisture affects the diffusion of substrates, enzymes, and products of enzymes, and thus it may impose diffusion limitations on enzymes and its substrates (Allison 2005).
- Drought may decrease enzyme production as biomass accumulation declines or increase production to satisfy nutrient requirements of the biomass in oxisol (Allison and Vitousek 2005).
- Stable potential enzyme activities may also be observed under drought, but this does not necessarily indicate that these enzymes are active in dry soils (Steinweg et al. 2013). Actually, microbial uptake is more sensitive to soil moisture than enzyme activity (Suseela et al. 2012).

- In contrast, a study revealed soil organic C, microbial biomass N, dehydrogenase, phosphatase, and different pools of arylsulfatase activities decrease significantly with increasing soil aridity in desert (Li and Sarah 2003a, b).

4.6 Effect of Environmental Modification on Soil Physical Properties

At present, very few reports are available around the world, studying the impact of different environmental modification on soil physical properties. Any environmental modifications are expected to have the potential to alter soil aggregation. But the types of shifts altering the aggregate stability and magnitude of change in factors (such as root biomass and fungal length) to alter aggregate stability along with the mechanism are uncertain and yet to be studied extensively under long-term CO_2 and O_3 exposure/atmospheric warming experiments. Continuous four years of exposure to enriched level of atmospheric CO_2 have no effect on water-stable aggregates, but it influenced labile C and belowground root biomass of five annual grassland species (Eviner and Chapin 2002), without affecting the aggregate size distribution classes (Dorodnikov et al. 2009; Saha et al. 2011). In contrast, the enriched level of atmospheric CO_2 has the potential to increase the soil aggregation due to enhanced root growth (Rogers et al. 1998; Sillen and Dieleman 2012). The enhanced root carbon inputs help to stabilize the soil microaggregates via enmeshment (Jastrow et al. 2005). On the other hand, the by-products of microbial activity, such as extracellular polysaccharides of bacteria or glycoprotein glomalin of arbuscular mycorrhizal fungi, can form, with the surrounding mineral particles, an organo-mineral sheath around the cells that leads to an increase in macroaggregates as an indirect additional effect. This mechanism supports the reported increase in water stability and size distribution of aggregates in serpentine field plots for three ecosystems after long-term exposure to elevated atmospheric CO_2 (Rilling et al. 1999; Rillig et al. 2002). Earthworms have the potential to promote the stabilization of increased labile carbon inputs in soil via soil aggregate formation, resulting from elevated level of atmospheric CO_2 enrichment (Sánchez-de León et al. 2014).

4.7 Case Studies: A Special Reference to India

Case Study I: (Kant et al. 2007).

Soil type: *Typic* Haplustept (old alluvium) at Indian Agricultural Research Institute, New Delhi

Crop: Wheat (HD 2687)

Treatments: (i) Ambient CO_2(~370 μmol mol^{-1}) in open-top chambers (OTC); (ii) Elevated CO_2 (600 μmol mol^{-1}) in open-top chambers (OTC).

Results: Pot experimentation showed a significant gain in all the active C fractions with elevated atmospheric CO_2 exposure over initial status. The order of average increase in these active carbon pools was dissolved organic C (49%)

>microbial biomass C (19%) >labile C (15.7%) >carbohydrate C (0.83%). The higher microbial activity in the wheat rhizosphere soil often concentrated during crown root initiation and anthesis stages, but reduced at crop maturity.

Case Study II: (Saha et al. 2011)

Soil type: *Typic* Haplustept at Indian Agricultural Research Institute, New Delhi

Crop: Pigeon pea (PUSA 992 and PS 2009)

Treatments: (i) Ambient CO_2(~390 μmol mol^{-1}) in open-top chambers (OTC), (ii) elevated CO_2(580 μmol mol^{-1}) in open-top chambers (OTC).

Results: At the end of crop season, a 3.2-fold increase in microbial biomass C was recorded with concomitant increase in labile C (20%) and carbohydrate C (71%) fractions under elevated CO_2. A significant rise in dehydrogenase activity and FDA hydrolysis activity further confirmed the increased microbial activity under elevated CO_2 treatment with no significant change in soil physical properties. Enrichment of atmospheric CO_2 resulted in more biologically active rhizosphere soil in pigeon pea without any genotypic variation. That ultimately resulted in greater soil CO_2 concentration and increased soil CO_2 flux possibly due to enhanced microbial respiration.

Case Study III: (Manna et al. 2013)

Soil type: Inceptisol of the Indian Agricultural Research Institute, New Delhi

Crop: Rice

Treatments: (i) Ambient CO_2 outdoor (~390 μmol mol^{-1}), (ii) ambient CO_2 (~390 μmol mol^{-1}) in open-top chambers (OTC), and (iii) elevated CO_2 (580 ± 20 μmol mol^{-1}) in open-top chambers (OTC). A broad-spectrum, systemic, and soil-applied fungicide “azoxystrobin” was applied to each pot at recommended dose (375 g a.i.ha^{-1}).

Results: Both elevated CO_2 and azoxystrobin, alone or in combination, have no impact on the soil dehydrogenase activity. Slight increase (1.8–2 °C) in temperature inside OTC shows similar microbial activities as in rice grown in outdoors and in OTC at ambient CO_2. Elevated CO_2 enhances soil microbial biomass (MBC) and alkaline phosphatase activity of soil. On the contrary, elevated CO_2 does not affect fluorescein diacetate and acid phosphatase activity. Authors suggest for a long-term study under varying levels of CO_2 to get the real effect of climate change on pesticide degradation.

Case Study IV: (Bhattacharyya et al. 2013a)

Soil type: Tropical alluvial soil (Aeric Endoaquept)

Crop and variety: Rice (cv. Naveen)

Treatments: The experiments were conducted in open-top chambers (OTCs). The four treatments were (i) UC, unchambered field (394 ± 10 μmol mol^{-1} CO_2); (ii) CC, ambient control chamber (394 ± 10 μmol mol^{-1}CO_2); (iii) CEC, chamber with elevated CO_2 (550 ± 30 μmol mol^{-1}CO_2); and (iv) CECT, chamber with elevated CO_2 (550 ± 30 μmol mol^{-1} CO_2) and elevated temperature associated with 2 °C higher temperature compared to ambient chamber.

Results: The soil enzymatic activities are significantly influenced by the exposure of elevated CO_2 and temperature throughout the plant growth stages. Dehydrogenase activity increases significantly under CEC and CECT. The highest dehydrogenase activity (1444 μg TPF g^{-1} day^{-1}) is seen in CECT treatment. Similar trend is observed in fluorescein diacetate (FDA) hydrolysis activities. The β-glucosidase activity increased with plant growth up to panicle initiation stage. The maximum activity (488.7 μg urea hydrolyzed g^{-1} h^{-1}) of urease was noted under CEC at the panicle initiation stage.

Case Study V: (Bhattacharyya et al. 2013b)

Soil type: Tropical rice soil (Aeric Endoaquept)

Crop and variety: Rice plants (cv. Naveen)

Treatments: The experiments were conducted in open-top chambers (OTCs). The four treatments were (i) UC, unchambered field (370 ± 20 μmol mol^{-1} CO_2); (ii) CC, ambient control chamber (370 ± 20 μmol $mol^{-1}CO_2$); (iii) CEC, chamber with elevated CO_2 (550 ± 30 μmol $mol^{-1}CO_2$); and (iv) CECT, chamber with elevated CO_2 (550 ± 30 μmol mol^{-1} CO_2) and elevated temperature associated with 2 °C higher temperature compared to ambient chamber.

Results: The enzyme activities in soil are affected by exposure to elevated CO_2 and also by the interactive effect of the elevated CO_2 and temperature throughout the plant growth stages. Maximum dehydrogenase activities are observed at the panicle initiation stage, which declined sharply at maturity. Throughout the cropping period, the dehydrogenase activity is significantly higher under CECT. The FDA activity is recorded at its maximum under CECT treatment (14.67 μg fluorescein g^{-1} soil h^{-1}) in panicle initiation stage. The β-glucosidase activities increased with plant growth and are the highest at panicle initiation stage compared to the other growth stages irrespective of treatments.

4.8 Adaptation Strategies

The most important challenge for agriculture in the twenty-first century is the need to feed increasing numbers of people – most of whom are in developing countries like us – while, at the same time, conserve the local and global environment in the face of limited soil and water resources and growing pressures associated with socioeconomic development and climate change (Tubiello 2012). To feed more mouths, somehow, mankind will face a certain effect of climate change. However, adaptation will be needed to protect livelihoods and food security under climate change situation. Proposed measures for adaptation of climate change are as follows (Howden et al. 2007):

(i) Modifying inputs (fertilizer, irrigation, etc.) and varieties (altering the timing or location of cropping activities) for increased resistance to heat, drought, flood, and salinization
(ii) Efficient irrigation services, avoiding waterlogging, nutrient leaching and erosion, promoting water harvesting, and soil moisture conservation
(iii) Integrated farming such as livestock raising and fish production in rice paddies with less environmental footprint
(iv) Promoting integrated pest and disease management, using resistant varieties

(v) Increasing use of climate forecasting to reduce production risk
(vi) Balance in livestock keeping with pasture production, pasture rotation, adjustment of grazing times, and change of forage and animal breeds
(vii) Improved forest management, including hardwood/softwood species mix, shifting to species or areas more productive under new climatic conditions, planning landscapes to minimize fire and insect damage, etc.
(viii) Introducing forest conservation, agroforestry, and forest-based enterprises for diversification of rural incomes
(ix) Altering the catch size and effort and improving the environment where breeding occurs, as well as reducing the level of fishing in order to sustain yields of fish stocks

4.9 Mitigation Options

Reducing emission of GHGs, enhancing removals, and avoiding emissions are the three pillars of mitigation strategy for climate change.

(i) For carbon dioxide:
  - Aggregation: Increase in stable microaggregates through the formation of organo-mineral complexes encapsulates C and protects it against microbial activities.
  - Humification: To sequester C in humus, addition of N, P, and S is needed.
  - Translocation into the subsoil: Translocation of SOC into the subsoil.
  - Formation of secondary carbonates: $CaCO_3$ and $MgCO_3$.
  - Burial of SOC-laden sediments: Transport of SOC-enriched sediments to depressed sites and/or aquatic ecosystems.
  - Plantation of deep-rooted plants: Horticulture and agroforestry.
  - Restoration of degraded lands: Adoption of conservation tillage and mulch farming techniques, soil and water conservation, and use of suitable crop rotations.
  - Reduced tillage: C may sequester under no-tillage.
  - Application of biochar: Organic material used up slowly under limited oxygen. Highly stable, porous, active surfaces.
  - Mineralogical control of soil carbon (Chatterjee et al. 2013).
  - Establishment of bioenergy plantation with a large potential for biomass production.
  - Afforestation of agriculturally marginal soil.
  - Growing species containing cellulose and other resistant materials.
  - Soil fertility management: Integrated use of fertilizer and manures, addition of compost and biosolids which stimulates soil biological activity and humification efficiency, and improving soil structure leading to increase in SOC sequestration and water management through irrigation can drastically increase SOC content.

(ii) For methane:
  - Upgrading the equipment used to produce, store, and transport oil and gas can reduce many of the leaks that contribute to CH_4 emissions. Methane from coal mines can also be captured and used for energy.
  - Reducing methane emission from rice field: Alternate wetting and drying, efficient rice variety, application of organic inputs under aerobic condition, crop rotation, and application of Mn, Fe, S, fertilizers.
  - Integrated rice and livestock systems: Use a highly digestible feed for livestock.
  - Better irrigation water efficiency.
  - Integrating animal manure waste management systems, including biogas capture and utilization.
  - Capture landfill CH_4.

(iii) For nitrous oxide:
  - Water management: Drainage increases the emission of N_2O.
  - Judicious application of N fertilizer (Pathak et al. 2016).
  - Application of nitrification inhibitors and slow-release fertilizers.
  - Integrating animal manure waste management systems.
  - Restoring land by controlled grazing.

4.10 Conclusion

It is evident that the positive feedback of the ever-increasing atmospheric GHGs often accounts for hastening the atmospheric warming rate even in a greater magnitude than the available model predictions. The impact of this global environmental change is expected to have a marked influence on the belowground soil processes. Unlike plant systems, the response of soil toward this environmental change is expected to be limited due to strong buffering capacity of the soil. The experimental reports based on short-term exposure of environmental modifications often ignore this fact. Short-term elevated atmospheric CO_2 enhances C accumulation on potential and belowground translocation of photosynthates toward the roots of different C_3 crop species by stimulating photosynthesis. For C_4 crop species, the scope is often limited. But, the overall C sequestration potential of any C_3-dominated ecosystem is often limited under sufficient moisture availability due to increased labile C fractions and enhanced soil microbial respiration with greater substrate availability from rhizodeposition. For long-term CO_2 exposure, the phenomenon is expected to be limited due to photosynthetic acclimatization as well as the soil buffering capacity. At present, such investigations are highly suffering from limited report availability for conducting long-term elevated CO_2 exposure impact experimentation on soil-plant-atmosphere continuum in India. Some reports are available under the temperate climate conditions of the European countries. But such reports have limited applicability for the tropical environmental condition in India. In addition, the modulating impacts of elevated temperature and other GHGs in conjunction to elevated atmospheric CO_2 levels are not yet widely studied. Majority of such available interaction studies are often confined into control chamber experimentation due to poor infrastructure facility, which is available to conduct such expensive research experimentation in India. Studies on GHG emissions have fetched immense popularity due to their increasing role in policy-making at national and international domain. In contrast, the GHG impact studies have no such direct impact on the policy formulation. But such impact studies often constitute the most essential tool to understand the ecosystem physiology that is useful to develop the prediction models of our future environment as well as different soil processes. It will be also useful to curve out the climate change adaption and mitigation strategies for our near future. The treasures of long-term impact research inventory on carbon stock and nutrient availability are yet to unveil in relation to our future crop productivity. Therefore, we have to realize the need to focus our future research thrust on the long-term impact studies of the environmental change on the belowground soil environment.

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Altitude Regulates Accumulation of Organic Carbon in Soil: Case Studies from the Hilly Ecosystem of Northeastern Region of India

5

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Abstract

A number of factors govern the accumulation and concentration of organic carbon in soil: land use management, the type of farming, vegetation, and climate (mainly temperature and rainfall); these determine the rate of carbon accumulation in and loss through soil. These governing factors are mainly associated with altitude, and in most cases, at low altitudes and at comparable altitudinal gradients, land use systems and land use management practices were dominant factors that altered variations in the accumulation of organic carbon in soil. However, at higher altitudes and in locations with considerable variation in altitudinal gradients, which may cause significant variation in climatic factors, rainfall and temperature were the dominant factors in determining organic carbon accumulation in soil. In general, land use systems (including phyto-biomass management) can mask the effects of altitudinal gradients (either significant or insignificant) on organic carbon accumulation in or loss through soil. In the northeastern region of India, it can be concluded that organic carbon (concentration and stock) in soil increases consistently with increase in elevation. The processes of carbon accumulation and loss involve complex interactions of multiple factors, which are reviewed in this chapter.

Keywords

Soil · Organic carbon · Altitude · Hill ecosystem

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5.1 Northeastern Region of India: At a Glance

The northeastern region of India is a large biodiversity hot spot (Nandy 2006) and comprises 26.1 million ha. The region receives, on average, more than 2200 mm of rainfall annually and is home to the world's wettest place (Cherrapunji plateau, in Meghalaya), with mean annual rainfall of over 11,000 mm during the monsoon season (June to September). In grasslands and dense forests at higher elevations (>2500 meter above mean sea level [MAMSL]), mean annual rainfall exceeds 3500 mm (Choudhury et al. 2016). Similarly, mean annual air temperature varies significantly across the region, from >22.0 °C at lower elevations (<250 MAMSL) to 13.0 °C at higher elevations (>2500 MAMSL); there are a few exceptions, however, such as subzero temperatures during winter in the Himalayan range (Sikkim peak) to temperatures as high as 38 °C in the plains and valleys of Tripura and Assam. As a result of this complimentary climate (mainly large amounts of rainfall and low temperatures), and by virtue of its geographical location within a hot spot of biodiversity, phyto-biomass is abundant in the region.

Nearly two-thirds of the total geographical area (TGA; 26.1 million ha) of the region has a predominantly undulating topography (mostly hills), and the steepness of the slopes varies from an imperceptible slope (in the Assam Valley and the Tripura plain) to extreme steepness (in Arunachal Pradesh, Meghalaya, Manipur, Nagaland, and Sikkim). Altitudinal gradient varies from as low as 6 MAMSL (Tura, Garo Hills) to as high as 8000 MAMSL (in Sikkim) (Choudhury et al. 2016) (Fig. 5.1). As a result, pedogenic processes, including soil formation, in the region are strongly influenced by interactional effects of climate, vegetation, and topography. In the valleys, soils are composed of transported materials (shale and recent alluvium deposits). In the hills, soils are derived mainly from sandstone, ferruginous sandstone, siltstone, mottled clay, sand, shale, thin seams of coal, and coal beds (Shillong Plateau, Jaintia Hills). The soils of the region are dominated by inceptisols, followed by entisols and ultisols. Other soil orders—alfisols and mollisols—also are found. The depth of soil across the study area varies considerably because of physiographic positions and slopes. Soils are deep in the valleys and moderately deep to deep in the hills, whereas soils are shallow (<20 cm deep) on degraded hills with steep slopes (Patiram and Ramesh 2008).

5.2 Land Uses and Land Cover in the Northeastern Region of India

Land uses and land cover in the northeastern region of India are distinctly different from those in the rest of the country (Table 5.1, Fig. 5.2). Nearly 60% of the geographical area in the region is forested (both dense and open forests). Because hilly topography prevails in two-thirds of the area, only 15.7% (4.1 million ha) of the TGA (26.1 million ha)—both uplands and lowlands—is under settled agricultural practices; shifting cultivation is practiced across nearly 3% of the TGA. Grasslands occupy a significant amount (> 6.0%) of the TGA. Wastelands and water occupy

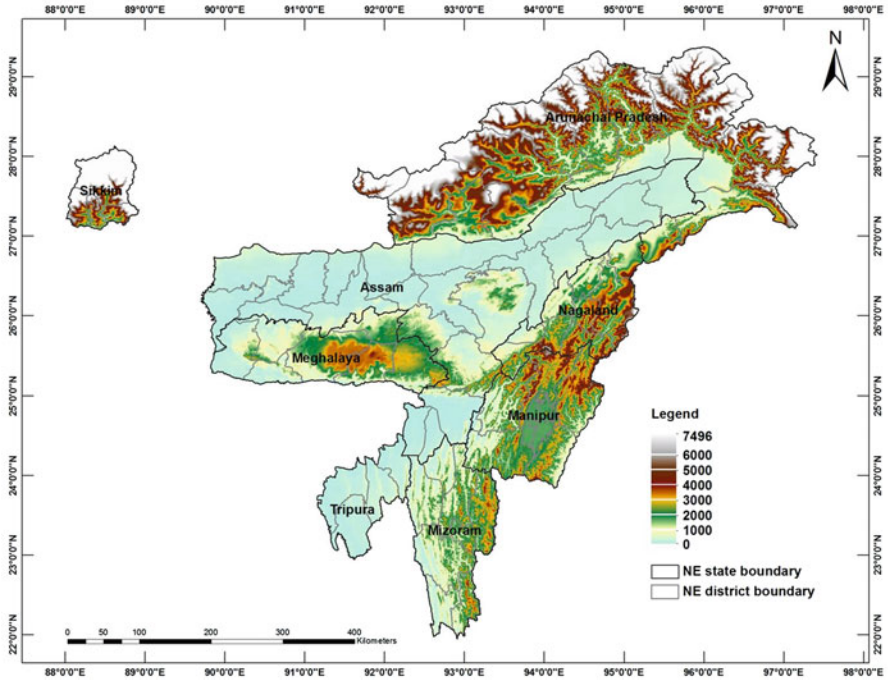

Fig. 5.1 Digital elevation map of the northeastern region of India at 30-m intervals. Derived by the authors from the Shuttle Radar Topography Mission (Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model). (Data from https://www.nrsc.gov.in/ [NRSC 2011])

nearly 6.5% and 4.5% of the TGA, respectively. In the Himalayan region of Sikkim, nearly 4% of the TGA remains under permanent snow cover (Choudhury 2014).

5.3 Distribution of Organic Carbon Concentration and Stock in Soil

The organic carbon (OC) concentration, as calculated through the use of the Walkley-Black method, is very high in surface soils in the northeastern Himalayan states (excluding Arunachal Pradesh and Mizoram), and both carbon concentration and carbon stock vary considerably, as presented in Tables 5.2 and 5.3. Of soils across the TGA (15.61 million ha) mapped by Choudhury et al. (2013), more than 98% had an OC concentration greater than 1%. Similarly, soil in more than 56% of the GA had an OC concentration of 1.5–3.5%, whereas OC was 3.5–5.5% in soil in 1.0% of the GA (Table 5.2). Among the six states mapped, soils from Sikkim were relatively rich in OC. Nearly 98% of the GA of Sikkim had an OC concentration greater than 2.5%; of that, 4.4% of the area recorded 3.5–5.5% OC concentration. Overall, soils from Tripura and Assam contained relatively little OC (1.0–1.5%),

Table 5.1 Land use patterns in the northeastern region of India

	States in northeast India								Total
	Arunachal Pradesh	Assam	Manipur	Meghalaya	Mizoram	Nagaland	Sikkim	Tripura	
GA (million hectares)	8.30	7.79	2.22	2.24	2.10	1.65	0.70	1.02	26.0
Land use (% of GA)									
Crops	2.93	37.27	7.78	8.93	4.41	11.5	9.78	17.6	15.7
Built up	0.46	0.71	1.69	3.73	0.82	2.23	0.24	8.22	1.37
Grassland	6.41	5.53	6.66	0.84	16.5	0.14	7.64	4.57	6.06
Dense forest	58.0	15.8	28.9	25.0	19.8	26.7	26.0	46.0	33.5
Open forest	14.9	24.4	35.6	42.5	44.4	37.6	10.4	9.24	25.4
PH	0.02	0.16	0.01	0.05	0.40	0.42	0.33	5.88	0.36
SC	1.83	0.30	2.79	3.33	12.5	9.08	0.00	2.44	2.88
Snow	9.51	0.00	0.00	0.00	0.00	0.00	36.7	0.00	3.98
Wasteland	3.92	4.58	14.5	13.9	0.19	11.0	8.04	4.89	6.22
Water	1.94	11.25	1.92	1.56	1.08	1.15	0.79	1.09	4.53

GA geographical area, *PH* plantation and horticulture, *SC* shifting cultivation
Adapted from Choudhury (2014)

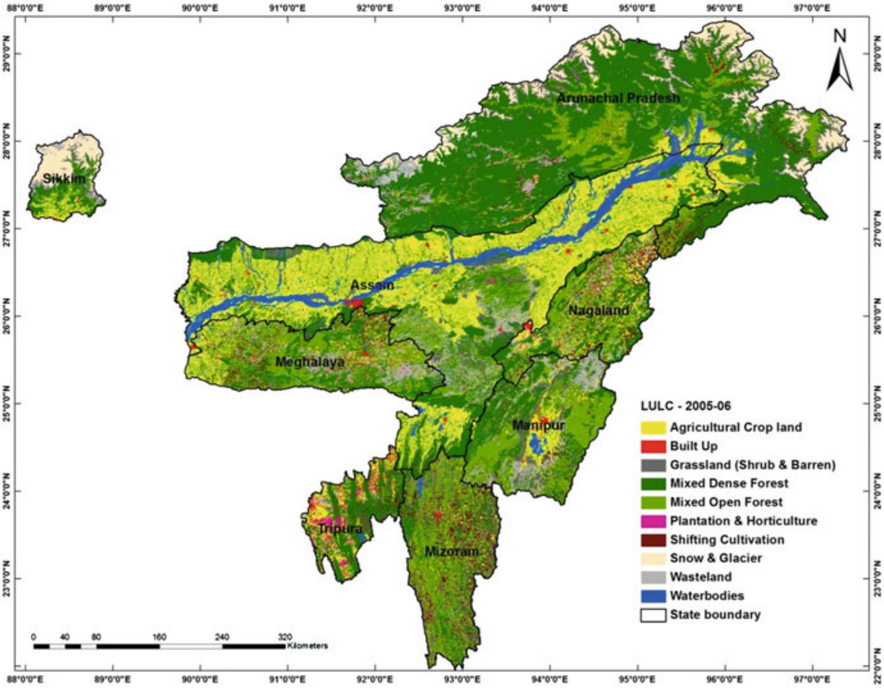

Fig. 5.2 Map of land use–land cover in the northeastern region of India, derived from data from multiple dates from the Indian Remote Sensing Satellite IRS-P6 LISS-III (2005–2006). (Source: https://www.nrsc.gov.in/ [NRSC 2011] and partly modified by the authors)

Table 5.2 Distribution of organic carbon (%) in soil[a] across the northeastern region of India

State	Geographical area (million hectares)	OC concentration (%) in soil				
		0.5–1.0	1.0–1.5	1.5–2.5	2.5–3.5	3.5–5.5
Assam	7.79	1.74	62.83	34.59	0.84	0.00
Manipur	2.22	0.00	2.93	71.63	21.80	3.64
Meghalaya	2.24	0.07	19.90	62.86	15.39	1.78
Nagaland	1.65	0.81	4.18	61.56	33.32	0.14
Sikkim	0.70	0.00	0.00	1.70	93.88	4.42
Tripura	1.02	7.55	89.03	3.42	0.00	0.00
Total	15.61	1.46	40.85	43.25	13.44	1.00

Data are the percentage of geographical area unless otherwise indicated

[a] Calculated using the Walkley-Black method

OC organic carbon

Adapted from Choudhury et al. (2013)

Table 5.3 Spatial distribution of organic carbon density in soils across the northeastern region of India

State	Geographical area (million hectares)	OC density in soil (Mg/ha)					
		10–20	20–30	30–40	40–50	50–60	60–80
Assam	7.79	19.40	65.31	13.26	1.86	0.17	0.0
Manipur	2.22	0.0	49.39	36.51	13.03	1.07	0.0
Meghalaya	2.24	1.42	49.51	42.56	4.06	1.72	0.73
Nagaland	1.65	1.71	40.43	57.51	0.35	0.0	0.0
Sikkim	0.70	0.0	0.0	7.17	81.98	10.86	0.0
Tripura	1.02	81.80	18.20	0.0	0.0	0.0	0.0
Total	7.79	15.39	52.16	24.30	7.07	0.97	0.13

Data are the percentage of geographical area unless otherwise indicated
OC organic carbon
Adapted from Choudhury et al. (2013)

whereas a significant amount of the soils in Nagaland, Manipur, and Meghalaya had an OC concentration of 1.5% or more. On the basis of percentage of GA with high OC concentration in soil, Sikkim had the most, followed by Nagaland, Manipur, Meghalaya, and Assam, with Tripura having the least (Table 5.2).

Similar to OC concentration, OC density in soil among the northeastern states follows the same order: Sikkim > Nagaland > Manipur > Meghalaya > Assam > Tripura (Table 5.3). Only Sikkim had a considerable amount of soil (>10%) with very high OC density (50–60 Mg/ha), whereas Tripura recorded the highest percentage of soil (81.8%) with relatively low OC density (10–20 Mg/ha) (Choudhury et al. 2013) (Table 5.3). Half of the GA in the region had OC density of 20–30 Mg/ha in soil, whereas one-fourth of the area had OC density of 30–40 Mg/ha in soil. Nearly 8.2% of the region (excluding Arunachal Pradesh and Mizoram) had OC density greater than 40 Mg/ha in soil.

5.4 Effect of Altitudinal Gradients on OC Concentration and Stock in Soil in the Northeastern Region of India

5.4.1 Case Studies from Northeastern States

5.4.1.1 Manipur

While studying the effect of secondary forest in shifting cultivated areas in the northeastern state of Manipur, Sarkar et al. (2015) recorded a significant effect of altitudinal gradient (821–1435 MAMSL) on OC concentration and stock in profile soils (0–45 cm deep) (Table 5.4). Climatic factors increased with an increase in altitude from 821 to 1434 MAMSL: rainfall increased by more than 400 mm, whereas temperature decreased by nearly 1 °C. As a result, OC concentration in soil increased significantly ($P < 0.05$) from 1.71% (at an altitude of 821 m) to 3.19% (at 1434 m) across areas of jhum cultivation with different fallow ages (from fresh jhum to stabilized jhum land left fallow for 5–33 years). Despite shallow soils with a

Table 5.4 Agro-physical parameters at a sit of shifting cultivation in Manipur State, India

Parameter	Chandanpokpi	Monsangpantha	Hengkot
Altitude (MAMSL)	821	1044	1434
Mean temperature (°C)	19.5	20.1	18.4
Rainfall (mm)	1089	1138	1506
Vegetation	Subtropical pine	Subtropical broad-leaf	Subtropical broad-leaf
Soils	Deep	Deep	Moderately shallow
Textural class	Clay like surface	Clay like surface	Loamy surface

MAMSL meters above mean sea level
Adapted from Sarkar et al. (2015)

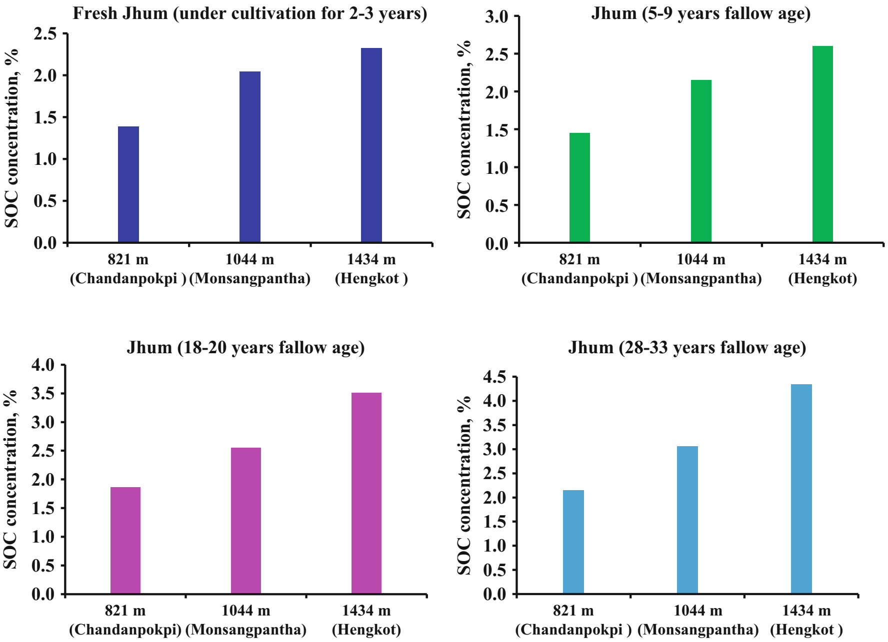

Fig. 5.3 Altitudinal variation on organic carbon concentration in soil left fallow for different periods under shifting cultivation in Manipur, India. (Adopted from Sarkar et al. 2015, modified by authors)

relatively coarse texture (loamy surface) and broad-leaf vegetation at a higher altitude in Hengkot (1434 MAMSL), OC concentration in soil was 1.66- to 2.0-fold higher than that in the relatively fine soil (clay like surface) at a low altitude (821 MAMSL) in Chandanpokpi (1.39–2.15%) across fresh and stabilized jhum with fallow periods ranging from 5 to 9, 18 to 20, and 28 to 33 years (Fig. 5.3).

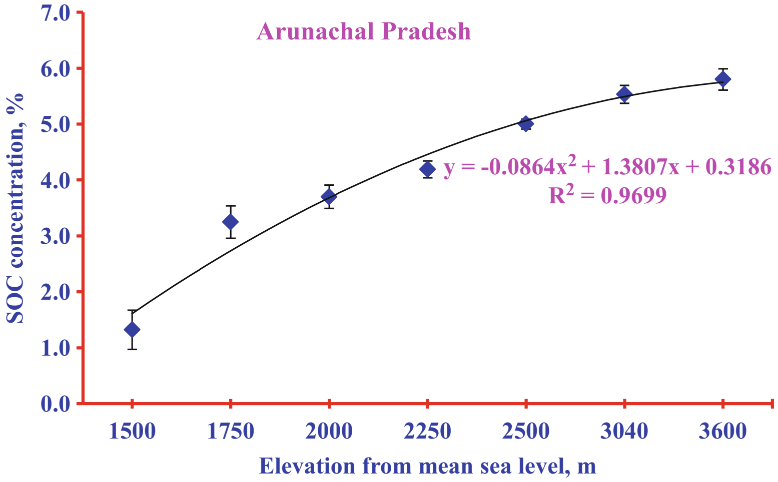

Fig. 5.4 Effect of altitudinal variation in organic carbon concentration in soil in Arunachal Pradesh

5.4.1.2 Arunachal Pradesh

Study of surface soils (0–15 cm deep) across different lands in the northeastern state of Arunachal Pradesh also revealed a consistent increase in OC concentration (from 1.32% to 5.8%) along altitudinal gradients (1500 to 3600 MAMSL). With an increase in elevation from 1500 (1.32% OC in soil) to 2000 MAMSL, OC concentration in soil increased more than 2.8 times, and with further increases in elevation by 250 up to 2500 MAMSL, OC concentration in soil increased by another 13–19%. At higher altitudes (>3000 MAMSL), OC concentration in the soil exceeded 5.5%, and the rate of increase was more than four times that of the baseline elevation (1500 MAMSL) (Fig. 5.4).

5.4.1.3 Mizoram

In another study in Mizoram State in northeastern India, we observed an irregular increase in OC concentration in soil as we moved from an elevation of 700 to one of 1800 MAMSL, across which land uses differed (e.g., agriculture, horticulture, shifting cultivation, grasslands) (Fig. 5.5a). At mid-altitudes (1200–1300 MAMSL), higher OC concentration was observed in soil than that at relatively higher altitudes (>1600 MAMSL). Similarly, clay content also reflected a strong positive correlation ($r = +0.68$) with OC concentration in soil along the altitudinal gradient (Fig. 5.5b).

5.4.1.4 Meghalaya

In a case study to assess and map surface soils within a 0.2 × 0.2 km area (at a 1:10,000–12,500 scale) in select districts of northeastern India (the South Garo Hills of Meghalaya and the Dhalai district of Tripura, Northeast India), Choudhury (2014)

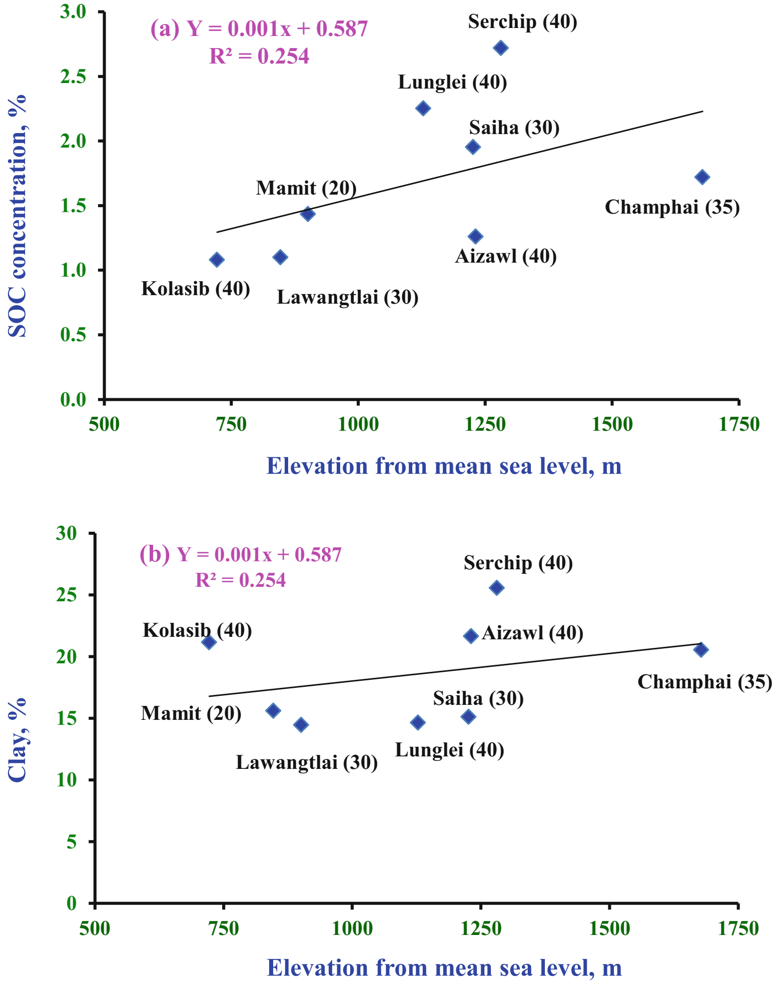

Fig. 5.5 Variation of (**a**) organic carbon concentration and (**b**) clay content in soils along an altitudinal gradient in Mizoram

observed a marginal decreasing trend in OC concentration in soil along an altitudinal gradient ranging from 6 to 120 MAMSL (Figs. 5.6a and 5.7a). Among soil properties, clay content strongly influences OC concentration in soil (Choudhury et al. 2016). In their study, Choudhury et al. observed that clay content also marginally decreases with an increase in altitudinal gradient (Figs. 5.6b and 5.7b).

Major reasons for this reverse trend were the masking effects of land uses and the marginal variation in altitudinal gradient (6–120 m), which does not sufficiently influence climatic parameters (rainfall and temperature). Lowland paddy fields and

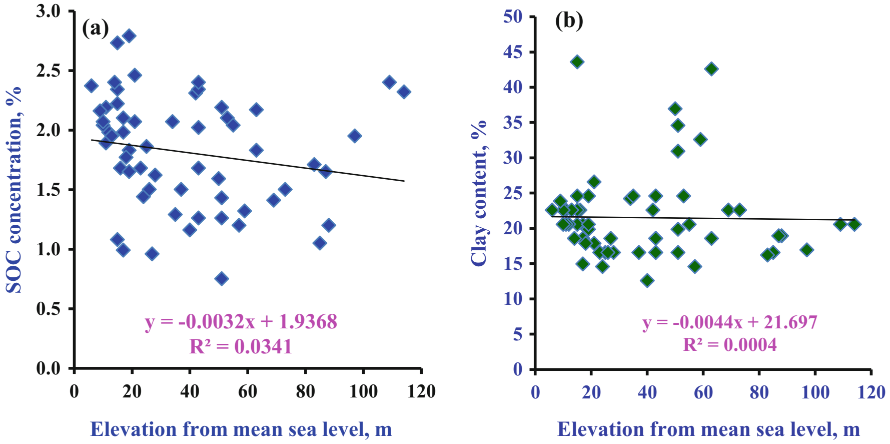

Fig. 5.6 Variation of (**a**) organic carbon concentration and (**b**) clay content in soils along an altitudinal gradient in Sibbari, Tura, Meghalaya

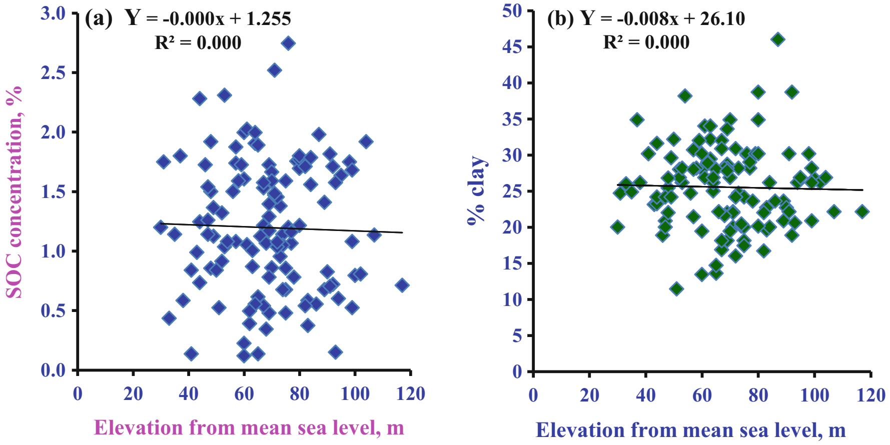

Fig. 5.7 Variation of (**a**) organic carbon concentration and (**b**) clay content in soils along an altitudinal gradient in Dhalai, Tripura

pond beds are the dominant land uses at lower altitudes (<20 MAMSL), whereas upland agriculture (maize and upland rice), horticulture (vegetables), and some plantation crops are the predominant land uses at relatively higher elevations (40–120 MAMSL). In addition to deposition from underground biomass (roots) in paddy fields, prevailing anaerobic conditions in paddy fields and pond bed soils cause the rate of decomposition of OC in soil to be slow. In contrast, low-input intensive cultivation of upland agriculture and horticulture crops at altitudes >40 MAMSL causes aerobic conditions, which favor relatively less accumulation of OC because of the faster rate of decomposition. Another important reason is that because of the effect of relatively lower altitudinal gradient (6–120 m) in this study than in other reported studies (6–3500 m) on increases in OC concentration in soil (Choudhury et al. 2016), important climatic parameters that are responsible for higher phyto-biomass production (rainfall) and decreases in the rate of mineralization/decomposition (temperature) are comparable across the study area. As a result, the influence of insufficient altitudinal gradient (6–120 m) cannot mask the prominent effect of land use on OC concentration in soil, and thus these concentrations along the altitudinal gradient showed a marginal decreasing trend in both the South Garo Hills in Meghalaya and the Dhalai district of Tripura.

In another case study, Basaiawmoit et al. (2015) reported an irregular increase in OC concentration and carbon stock in soil with an increase in elevation from mean sea level (880–1880 m) for both surface (0–15 cm deep) and subsurface (15–30 cm deep) soils in agricultural fields with different nutrient management practices in the northeastern state of Meghalaya (Fig. 5.8a, b). This variation in OC concentration and stock in soil suggests the partial effect of altitudinal gradient on climatic factors (mainly rainfall and temperature). As a result, in addition to differences in agricultural and nutrient management practices, mineralization and accumulation of OC concentration in soil were affected by the variation in climatic factors, and thus OC concentration and carbon stock in soil also vary along the altitudinal gradient.

5.4.1.5 Assam

Choudhury (2016) studied the spatial variability of OC concentration and stock in soil (at a scale of 1:50,000) for surface and profile soils (56–225 cm depth) in Barak Valley, Assam. Analysis of the OC concentration in soil samples collected from an altitudinal gradient of 7–140 MAMSL revealed that OC concentration in both surface and profile soils (weighted mean) decreased marginally along the altitudinal gradient (Fig. 5.9 a, b). Most of the soils at low altitudes (<30 MAMSL) were collected from lowland paddy fields or fallow fields, whereas soils at higher altitudes (>70 MAMSL) were collected from uplands (fallow fields, crops, trees). Low-input intensive cultivation prevails in the uplands and in lowland paddy fields, but relatively anaerobic conditions in the lowland paddy fields favor accumulation of more OC in soil than do the aerobic conditions of the uplands. Climatic variables (rainfall and temperature) along the altitudinal gradient did not vary significantly and were comparable across the study area. As a result, altitudinal gradient does not influence the OC concentration in surface and profile soils with comparable land management practices across the study area, and thus OC concentration in soil marginally decreased as elevation increased.

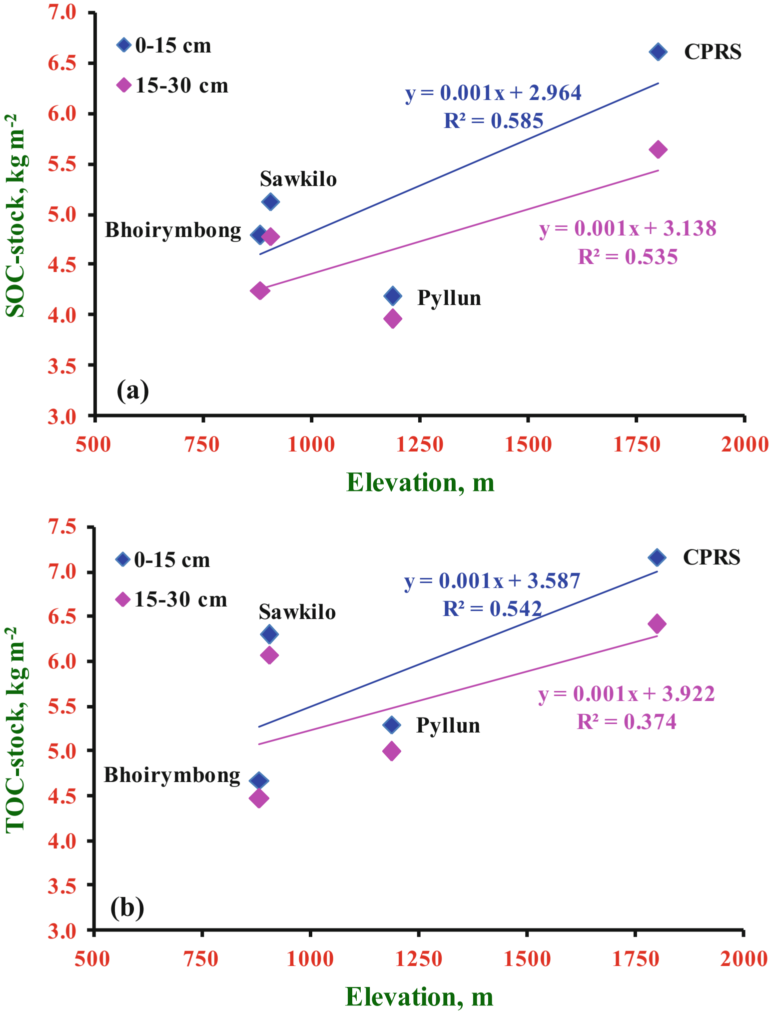

Fig. 5.8 Variation of (**a**) organic carbon stock and (**b**) Total Organic Carbon (TOC) stock in soils along an altitudinal gradient in Ri-Bhoi and East Khasi Hills, Meghalaya

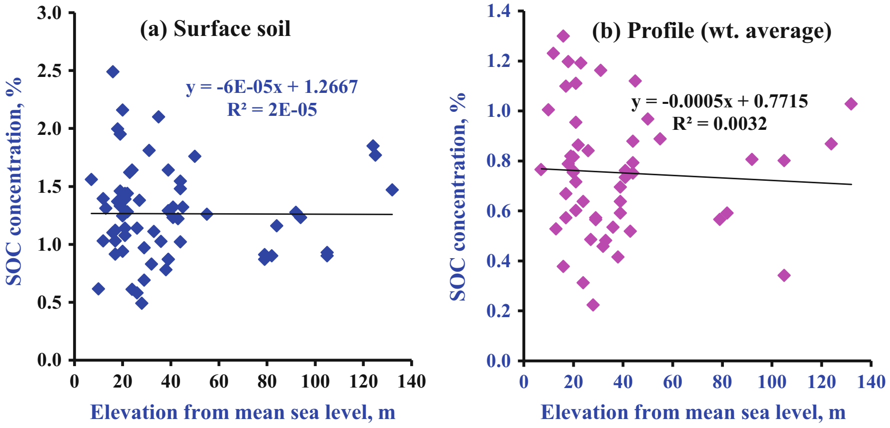

Fig. 5.9 Variation of organic carbon concentration in (**a**) surface soils and (**b**) profile soils along an altitudinal gradient in Barak Valley, Assam

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Part II

Making Interaction Favourable Through Management Interventions

Managing Photothermal Environment for Improving Crop Productivity

6

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and Harpreet Singh

Abstract

The difference between the energy absorbed by the earth's surface from direct incoming solar radiation and the energy reradiating back to the space as reflected solar radiation from soil and leaf surfaces will contribute to "radiative forcing" and creates a typical "photothermal" environment in the atmosphere. This photothermal environment is gradually changing due to several anthropogenic and natural causes leading to increase in aerosols and other air pollutants coupled with frequent occurrence of extreme temperature events. This change in the photothermal environment is being manifested through decreased photosynthetically active radiation (PAR) received at earth's surface by more than 6% and nearly doubling in the rate of increase in atmospheric temperature in the last 50 years. Consequently, crops' response to fluctuations in the magnitude and distribution of these two weather elements, i.e., light/radiation and temperature play an important role in determining its growth and development. Besides, response of the crops to these extremes also depends on the genetic constitution, physiological make-up (C3, C4, and CAM plants; light sensitivity) and stages of growth of different crop species. Therefore, in view of the above facts, the target

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to improve crop productivity to cater the demand of ever-growing population can only be achieved by taking adaptation measures through various management interventions including manipulating the photothermal environment. This chapter describes the aspects of solar radiation, radiative forcing, low and high temperatures, photothermal quotient, etc., which have direct and indirect impacts on crop production and also the possible photothermal-related management strategies for enhancing crop productivity.

Keywords
Photothermal · PAR · Temperature · Radiative-forcing · Crop · Productivity

6.1 Introduction

Soil, water and solar energy are the basic resources required for crop production in general, and now it is a concern for utilizing plant structural (or morphological) and plant functional (or physiological) responses with soil and climatic conditions to produce higher yield per unit land area. Initially studies on climate change and its potential impact on agriculture mainly focused on increasing levels CO_2 (Curry et al. 1990), but later on it was reported that changes in solar radiation and temperature need to be studied to evaluate their impacts on crop productivity (Ahmed et al. 2011a, b). For example, rice and wheat yields are significantly reduced/affected due to solar radiation and temperature variations (Ahmed et al. 2010; Bal et al. 2004; Mallick et al. 2007; Li et al. 2010) and even to the tune of 0.6–8.9% reduction per 1 °C rise in temperature has been recorded (Lobell and Field 2007).

Solar radiation influences crop yield by exerting its impact on gross and net assimilation and ultimately biomass production. Irradiation emitting from sun and reaching the Earth's surface invading different layers of atmosphere forms a typical photoenvironment which governs the photosynthetic process (Monteith 1973). Besides, it also creates a thermal environment of atmosphere that supplies the required heat units indispensable for phonological advancement of crops. Therefore, it can be said that this photo- and thermal environment of the atmosphere is directed by global solar radiation which influences gross photosynthesis, tissue respiration and thereby net photosynthesis. Cumulative effect of photo- and thermal environment can be measured through different indices like photothermal unit (PTU) and photothermal quotient (PTQ). It has been generalized by different researchers that a higher solar irradiance coupled with lower atmospheric temperatures can satisfy the congenial condition for higher net photosynthesis by increasing gross photosynthesis and lowering sink respiration, ultimately leading to higher yield (Mukherjee et al. 2014). Instead of that, crops are increasingly getting exposed to the reverse situation (lower solar irradiance and higher ambient temperature) due to climate change scenario (Bal and Minhas 2017).

Temperature is another key determinants for the rate of plant development. The developmental stages of the determinate crops shorten due to warmer temperature are responsible for reduction in crop yield (Craufurd and Wheeler 2009). Crop productivity can negatively be influenced by higher temperature indirectly through phenological acceleration (Menzel et al. 2006; Wang et al. 2008; Lobell et al. 2011) with less time for accumulating biomass (Menzel et al. 2006). As immense attention on climate change impacts on crop production has been received over the last decades (Parry et al. 2004; Tao et al. 2008), understanding the relationship between climate and crop yield is thus fundamental to identify possible impacts of future climate and to develop adaptation measures. The global average temperature has increased by about 0.13 °C per decade since 1950 (IPCC 2007a). Significant warming trends in the Himalayan and Tibetan regions, generally higher than the global average, are reported in the literature (Hu et al. 2013). Furthermore, the rate of warming is generally larger at the higher elevation (Sharma et al. 2009). Such warming trends in the world's largest and highest mountain system will obviously influence the glacier and snow dynamics, leading to changes in water resources availability, particularly during spring and autumn (Maskey et al. 2011). At the Koshi river basin, Bhatt et al. (2013) observed significant impact of growing season temperature and precipitation on crop production in rice, maize and wheat. There were warming trends in growing season mean temperatures of rice, maize and wheat over the last few decades with clear evidence of negative impacts on yields. However, at some high-elevation areas, positive impacts of warming are also observed on rice and maize yields. If the observed trends in temperature continue in future, the impact is likely to be mostly negative on crop production in the basin.

Considering the important roles of solar radiation and temperature on growth and development of plants under changing climate, it is indespensible to understand the likely effects of each of these factors, deviating from their optimum levels in order to frame suitable strategy for sustaining crop production. Therefore, specific genetic factors with known physiological effects can be tied directly and quantitatively to create variation in phenology. With such a mechanistic understanding, scientists can better predict phenological responses to novel seasonal climates. As extreme climatic events are becoming more frequent and unpredictable, understanding crop responses to these events is also essential to cope up with anticipated changes in climate. The ultimate aim is to insulate future farming and food production system from a range of abiotic stresses to make the system more resilient to the direct and indirect consequences of a progressively changing climate.

6.2 Effect of Solar Radiation on Crop Production

Solar radiation is radiant (electromagnetic) energy emitted by the sun. When sunlight reaches the Earth, it is distributed unevenly in different regions due to reflection, scattering and absorption. At noontime, solar radiation reaches the ground almost vertically in the tropical zone (0°–23.5° N/S) due to which this region is very warm and evaporates more water. The air of this zone is often moist resulting in dense and frequent cloud covers which reduce the effect of solar radiation on ground temperature. The highest solar radiation receives in summer with relatively thin cloud cover at subtropics zone (23.5°–40° N/S). These regions receive lower moisture that's why the effect of solar radiation increases. This is the reason that why in this zone, most of the deserts in the world are situated. The solar radiation in these regions increases significantly, and it can momentarily be moist and very cool during winter season. The radiation reaches with a smaller angle in temperate zone (40°–60° N/S), and hence, the average temperature is much cooler than on the subtropics. The polar area (cold zone at 60°–90° N/S) receives less heat through solar radiation.

The solar radiation provides light and heat for the Earth and energy for photosynthesis. This radiation consists of ultraviolet, visible and infrared bands with 8.3, 42.3 and 49.4% contribution, respectively. This radiant energy is necessary for the metabolism of environment and its inhabitants. Each of these bands has a different impact on the environment. The bands range between 400 and 700 nm best suited for photosynthesis and are also known as photosynthetically active radiation (PAR). Varlet-Grancher et al. (1993) reported that plant is employed around 50% of incident radiation to perform photosynthesis. The photosynthesis majorly occurred in leaves, and it depends on the amount of solar radiation intercepted by plant canopy. Further, this is influenced by a number of factors, viz. reflection of light from surface of the leaf, chlorophyll concentration and thickness of the leaf, angle of the leaf, elevation of the sun and distribution pattern of direct and diffused radiation. Both types of radiations have received at the upper surface of leaves, whereas a small portion of direct solar radiation has intercepted at lower leaves. The reflected and transmitted solar radiation from leaves and surface of the soil indicated more significance of diffused solar radiation in the lower leaves (Matloobi 2012).

The light intensity (Ali et al. 2005), duration (Starr et al. 2000) and quality (Wassink and Stolwijk 1956) of solar radiation are important for plant processes. The site of latitude is an important and integrative environmental driver, and it is associated with variations in temperature regimes, photoperiod and radiation intensity, all of which determine growth and development (Craufurd and Wheeler 2009) and ultimately productivity. In the last five decades, air pollutants, aerosols and population density increased dramatically, and, as a result, solar irradiance decreased by more than 6% per decade (Li et al. 2005; Che et al. 2007) and photosynthetic active radiation by 1.3% (IPCC 2007a, b).The global radiation has been reduced by 1.4–2.7% per decade at places between 25 and 45°N (Ramanathan and Feng 2009). Hume and Cattle (1990) also reported that the solar radiation received at the surface will be variable geographically, and on an average, it is expected to decrease slightly by about 1%.

In many parts of the world including India, growth of infrastructure sector, vehicular pollution, agricultural residue burning have caused significant solar dimming (Ohmura 2006). This solar dimming (decrease in global radiation) has become a major challenge to crop production in many parts of the world (Mu et al. 2010). Aerosols influence the solar radiation both directly and indirectly through their various sizes and thus their different optical and physical properties. The reduction in light causes leaf senescence and negative association with grain yield (Talukder et al. 2014). The effects of low solar radiation on crop production are described in Table 6.1.

Table 6.1 Effects of low solar radiation on different crop production

Crop	Light intensity	Effects on plant	References
Potato	Low	Increased the leaf area in potato	Singh (1988)
Rice	Low	Plant height increased by 31%	Jadhav (1987)
	Low	Reduced dry matter and yield	Singh et al. (1988)
	Low	Sterile and defective caryopses	Borah and Bakuah (1995)
	Low	Enzymatic activities of starch are suppressed, and amylase, sucrose and starch contents in caryopsis are decreased	Li et al. (2006), Liu et al. (2006), Wang et al. (2013a, b)
	Low	Affects grain nitrogen and amino acid metabolism, increase levels of protein in caryopsis	Ren et al. (2003)
	Low	Reduction in chloroplast ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCo) activity	Shi et al. (2006)
	Low	Decrease in photosynthetic assimilates and dry matter translocation. Higher chlorophyll b and lower chlorophyll a/b content in leaves	Zhu et al. (2008)
Soybean	Low	Decreased shoot dry weight, grain yield	Kakiuchi and Kobata (2004, 2006)
	Low	Decreased photosynthesis, grain yield in determinate genotypes compared to semi−/indeterminate genotypes	Bhagat et al. (2017)
	Low	Grain yield significantly decreased under the low light intensity	Polthanee et al. (2011)
Cotton	Low	Adaptation of leaves to the low light environment to intercept more light energy	Zhao and Oosterhuis (1998)
Wheat	Low	Increased chlorophyll and lutein contents but decrease in net photosynthetic rate (Pn)	Zheng et al. (2011)
	Low	Accelerate carbon remobilization from vegetative tissues to the grains, leading to an acceleration of the grain-filling rate	Li et al. (2010)
Tobacco	Low	Increased plant height, contents of free water, chlorophyll, total nitrogen, and protein in leaves while stem circumference, dry weight/fresh weight ratio, leaf thickness, specific leaf weight, and dry matter accumulation decreased	Yang et al. (2007)
Chrysanthemum	Low	Increased plant height	Wang et al. (2009)
Peanut	Low	Leaf chlorophyll content, actual PSII photochemical efficiency and maximum PS II photochemical efficiency (Fv/Fm) was increased, while the Chl a/b ratio and photosynthetic rate (Pn) decreased	Zhang et al. (2009)
Sugarcane	Low	Reducing tons of cane and sugar per hectare	Gilbert et al. (2004)

6.3 Climate Change and Radiative Forcing

Climate change can be defined as potential shifts in long run means and extremes of climatic variables like atmospheric temperature, precipitation, solar radiation etc. The potential impact of changing climate on photothermal environment can be judged by a unique index known as radiative forcing. Radiative forcing is a measure of the influence factor in altering the balance of incoming and outgoing energy in the Earth-atmosphere system and is an index of the importance of the factor as a potential climate change mechanism (IPCC 2007a, b). Radiative forcing is expressed in watt per metre square (W/m^2). Ramaswamy et al. (2001) define it as the change in net (down minus up) irradiance (solar plus longwave, in W/m^2) at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium but with surface and tropospheric temperatures and state held fixed at the unperturbed values. The components which contribute to radiative forcing are long-lived greenhouse gases (carbon dioxide, methane, nitrous oxide, halocarbons etc.), ozone, stratospheric water vapour, surface albedo, total aerosol and solar irradiance. Radiative forcing can be related through a linear relationship to the global mean equilibrium temperature change at the surface (ΔT_s): $\Delta T_s = \lambda RF$, where λ is the climate sensitivity parameter (Ramaswamy et al. 2001).

Due to higher atmospheric temperature, evaporation from the water bodies increases causing increased water vapour content in the atmosphere. The Third Assessment Report of IPCC (2001) revealed long-term increase in stratospheric water vapour content and claimed to have substantial radiative effect. This water vapour forms a part of aerosol and poses positive radiative forcing impact by warming the atmosphere. Presently, there are 14 years data of global stratospheric water vapour measurements from Halogen Occultation Experiment (HALOE), and continued balloon-based measurements are available suggesting a sustained long-term increase in stratospheric water vapour content of around 0.05 ppm/year from 1980 to 2000. Forster and Shine (2002) and Smith et al. (2001) estimated a + 0.12 to +0.2 W/m^2 per decade range for the RF from the change in stratospheric water vapour, using HALOE satellite data. Besides its impact on aerosol formation and positive radiative forcing, stratospheric water vapour also plays a key role in governing cloud cover percentage and thus influencing total solar irradiance (TSI) (Fig. 6.1).

6.4 Effects of Temperature on Crop Production

The changes in global environment has become faster due to increase in human interference. Its effect on increase in greenhouse gases, related increase in atmospheric temperature and loss of natural habitats has led to further changes in ecosystems of the world. The primary cause of global warming is the emissions of higher levels of CO_2 and other heat-trapping gases in the atmosphere (Jones and Briffa 1992). Hingane and his team (1985) noticed that during the twentieth century until the 1980s, there was increase in mean annual temperature by 0.4 °C per 100 years in

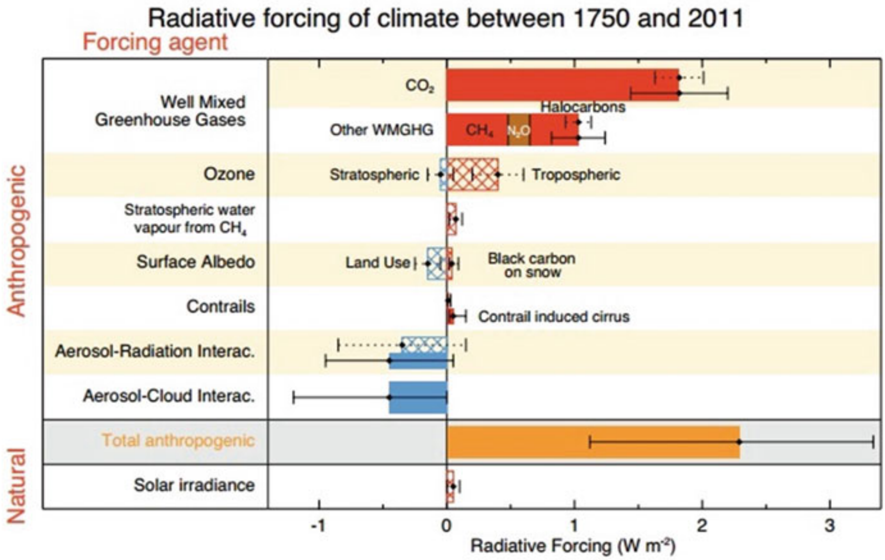

Fig. 6.1 Summary of the principal components of the radiative forcing of climate change. The values represent the forcing in 2011 relative to the start of the industrial era (about 1750). Human activities cause significant changes in long-lived gases, ozone, water vapour, surface albedo, aerosols and contrails. The only increase in natural forcing of any significance between 1750 and 2011 occurred in solar irradiance. Positive forcing leads to warming of climate, and negative forcing leads to a cooling. The thin black line attached to each coloured bar represents the range of uncertainty for the respective value (IPCC 2011)

relation to the Indian context. Similarly, the rise in mean annual temperature over the last century is 0.5 °C (Kothawale and Rupa 2002). The increase and decrease in temperature have major effects on plant growth and development.

Plants exposed to high and low temperature experience stress. There are many physiological injuries which have been observed under the exposure of high temperature, viz. inhibition of root or shoot growth or damages in fruit, leaf abscission and senescence and scorching of leaves and stems, which consequently escort the reduction in plant production and productivity (Vollenweider and Günthardt-Goerg 2005). Plant fertility is significantly reduced due to increase in temperature as reproductive development stage is more receptive to higher temperatures as compared to the vegetative stage (McKee and Richards 1998). In general if seedling and reproductive stages are exposed to high and low temperatures, crop production gets affected. Table 6.2 has shown that the C_3, C_4 and CAM plants suffer from high and low temperature stress at different stages of crop growth.

Table 6.2 Response of C_3, C_4 and CAM plants to high and low temperature stress conditions

Crop	High temperature stress	Low temperature stress	Affected growth stage	Effects on plant	References
C_3 plants					
Rice		13 °C for 15 days	Flowering stage	Reduction in the number of panicles, length of panicle, and the number of full, empty, and total grains	Ghadirnezhad and Fallah (2014)
		Above 12 °C	Early stage of crop growth	Breakdown of tissue and appearance of tissues as water soaked, desiccation, lesions, wilting, necrosis, reduction in leaf expansion, surface chlorosis	Wen et al. (2002)
		15/10 °C (D/N) for 2 weeks	Seedling stage	50% reduction in total chlorophyll content	Aghaee et al. (2011)
		At 11 °C	Reproductive stage	Sterile and malformed spikelet, incomplete panicle emergence, spikelet degeneration symptom, delayed heading, abnormality in panicle initiation	Nahar et al. (2009a, b)
	Above 33.7 °C		Reproductive stage	Induce sterility	
	39 °C/30 °C (day/night)		Microspore stage	Reduced spikelet fertility	Endo et al. (2009)
Soybean	Above 30–35 °C (day)		Flowering times	Seed set on male sterile, female fertile plants decreased	Wiebbecke et al. (2012)
	37/27 °C (day/night)		Flowering stage	Lower pod setting	Kitano et al. (2006)

Apple	Above 22 °C		Reproduction phase	Increases the fruit size and soluble solids but decreases firmness	Warrington et al. (1999)
Citrus	Above 30 °C		Reproduction phase	Increased fruit drop	Cole and McCloud (1985)
	Above 33 °C		Fruit development	Reduction in brix (sugar content), acid content, and fruit size	Hutton and Landsberg (2000)
Peanut	Above 36 °C for 1 day		Fruit development	Reduced fruit set	Prasad et al. (2001)
	Above 32/22 °C (day/night)		Reproduction phase	Poor pollen viability causes lower seed setup, and decrease in seed growth rates causes smaller seed size and decrease in shelling percentages	Prasad et al. (2003)
Tomato	Above 32/26 °C (day/night)		Flowering phase	Germination of pollen grains was lowered	Sato et al. (2000)
Cotton	Above 32 °C		Boll development	Boll growth decreases significantly, and fruit was dropped 3–5 days after blossoming	Reddy et al. (2000)
		Below 20 °C	Germination stage	Reduced germination percentages	Krzyzanowski and Delouche (2011)
Wheat	Above 20 °C at night		Reproduction phase	Decreased spikelet fertility, grains per spike, and grain size	Prasad et al. (2008)
	Very HT 45 °C		Germination stage	Embryo damage and cell death causes not adequate germination rate	Essemine et al. (2010)
	At 31.9 °C (night)		Grain filling stage	Decrease in photosynthetic rate (by 22%) and chlorophyll content (by 8%)	Prasad et al. (2011)

(continued)

Table 6.2 (continued)

Crop	High temperature stress	Low temperature stress	Affected growth stage	Effects on plant	References
		Below 8–10 °C	Germination stage	Germination is drastically hampered	Zabihi-e-mahmoodabad et al. (2011)
		3 °C for 48 h and 72 h	Vegetative stage	Decreased levels of Chl, CO_2 assimilation and transpiration rates	Yordanova and Popova (2007)
Mung bean	40/30 and 45/35 °C (day and Night)		Vegetative stage	Reduction of shoot and root growth	Kumar et al. (2011)
Barley	30 °C /25 °C (day and Night)		At five leaf stage	Decrease in anther and exogenous auxin restored male sterility	Sakata et al. (2010)
Strawberry	30/25 °C (day and Night)		Reproduction phase	Reduction in quantity of inflorescences, flowers, and fruits	Ledesma et al. (2008)
	24–32 °C		Reproduction phase	Reduces flower formation and fruit quality	Klamkowski and Treder (2008)
Coffee		Reduction in temperature of 0.5 °C day^{-1}, from 25/20 °C to 13/8 °C	Vegetative stage (for 24 days)	Increase in zeaxanthin; reduction in chlorophyll content, lutein content, α/β-carotene ratio	Partelli et al. (2009)
Apple	Above 22 °C		Reproduction phase	Increases the fruit size and soluble solids but decreases firmness as a quality parameter	Warrington et al. (1999)
Chickpea	32/20 °C (day and Night)		Flowering stage	Decrease of sugars in anther	Kaushal et al. (2013)

C_4 plants					
Maize	Above 35 °C		Pollination stage	Pollen viability decreases	Dupuis and Dumas (1990)
	Above 35 °C		Endosperm division phase	Kernel growth rate was reduced along with final kernel size	Jones et al. (1984)
	Above 30 °C		Grain filling	Damaged cell division, amyloplast replication and reduced the size of sink	Commuri and Jones (2001)
Sorghum	Above 36/26 °C (day/night)		Reproductive phase	Decreased pollen production, pollen viability, seed set	Jain et al. (2007a, b)
	40/30 °C (day/night)		Reproductive phase	Decreased seed yield	Prasad et al. (2006) Djanaguiraman et al. (2010)
Mustard		Below 10 °C	Germination stage	Reduce germination percentage, growth and premature stem elongation, seed diameter. Extensive white patches, white reticulation, red-brown pigmentation and folded seed	Angadi et al. (2000)
CAM plants					
Pineapple	Above 32 °C	Below 15 °C	Damage canopy, delay maturity and cause the fruit more acidic	Fruit development and retard growth	SweteKelly and Bartholomew (1993) Malezieux et al. (1994)
Cactus (*Opuntia bigelovii*)	44 °C	−4 °C		50% inhibition of nocturnal acid accumulation	Nobel (1983)

6.5 Climate Change and Photothermal Quotient

There is a direct impact of photothermal quotient (PTQ) on crop production. The PTQ can be defined as the ratio of total solar radiation in MJ m^{-2} day^{-1} to the mean daily temperature minus a base temperature (4.5 °C for spring wheat). Nalley et al. (2009) identified PTQ to improve the explanatory power of statistical regression models on grains per metre square (GM), grain weight (GW) and yield under climate change scenario. The assessment of climatic variables such as PTQ, solar radiation and temperature could be done to see their impact on crop life cycle, and quantitative relationship could be developed between climatic variables and crop production. Development of models as new adaptation and mitigation strategies by understanding the biophysical impact of climate change on wheat crop growth kinetics has been found to be significant for attaining yield sustainability. Loomis and Amthor (1996) concluded that photosynthesis is the source through which crop growth and its production were derived and the photosynthesis dependent on receipt and capture of solar radiation only in the form of direct or diffused. Therefore, to establish relation between solar radiation and PTQ in wheat crop growth and yield, based on the original field data, the development of regression model is essential. Yield is directly proportional to the PTQ with the condition that rests of all the resources are available at optimum. Since, PTQ fulfilled the crop light, temperature and solar radiation requirement, so it is the main limiting factor which determines the crop adaptation under specific environments. According to the varying climate of experimental site, the management such as Planting Windows option may be a tactical measure for the adjustment of PTQs. Adaptability of wheat genotype based upon its relationship with PTQ knowledge for a particular climate zone can be recommended to minimize losses in the yield due to extreme climatic events (Ahmed et al. 2011a, b).

Demotes and Jeuffroy (2001) used three variations of PTQ: 45 days before to 0 days after 50% anthesis, 30 days before to 0 days after 50% anthesis and 20 days before to 10 days after 50% anthesis. They concluded that PTQ accumulated between 45 days before and 0 days after 50% anthesis was superior to PTQ accumulated between 30 days before and 0 days after 50% anthesis, which was again superior to 20 days before to 10 days after 50% anthesis. Ahmed et al. (2011a, b) studied the effect of photothermal exposure on spring wheat in terms of PTQ calculated in daily basis by the formula as stated above and adding the daily PTQ from germination to anthesis and maturity to get the PTQ1 and PTQ2, respectively. They observed that grain number per m^2 is highly correlated ($R^2 = 0.88$) with PTQ1. GM2 increased from 5000 to around 20,000 linearly with an increase of PTQ1 (PTQ accumulated from germination to anthesis) from 110 MJ/m^2/day/°C to 160 MJ/m^2/day/°C. The same trend was noticed for PTQ2 (PTQ accumulated from germination to maturity). Similarly, Tubiello et al. (2002) predicted that early planting of winter wheat and irrigated maize in Fargo, ND, and Glasgow by 2–3 weeks will yield similar as current level of production and thus can avoid adverse effect of high temperature during post-anthesis period. Likewise, early planting of different crops like sugar beet, potato, etc. (Donatelli et al. 2002) has been shown as an adaptation for minimizing ill effects of climate change in crop production.

6.6 Management of Photothermal Environment

It is evident that photothermal conditions of the atmosphere are changing gradually due to climate change. Therefore, to cope up with this condition, some crop production strategies have to be formed out which will show resilience to the changing photothermal scenario.

6.6.1 Adjustment of Date of Sowing or Planting

Decision regarding when to plant a crop should be made according to availability of soil moisture, likely occurrence of temperature extremes, distribution of rainfall and of course radiation scenarios of the atmosphere. Thermo-sensitive crops like wheat respond well to the photo- and thermal environment to which they have been exposed. A number of field studies indicated that higher number of grains per metre square in wheat is associated with higher solar radiation and lower atmospheric temperature prior to anthesis period. This combined effect of solar radiation and atmospheric temperature can be better explained by an index called photothermal quotient (PTQ). The autumn sown irrigated spring wheat attains its highest theoretical sink capacity if the crop is planted at time which ensures its anthesis when the highest PTQ prevails. This results in higher grain number per m^2 due to exposure to higher radiation during pre-anthesis period as well as higher grain weight due to low temperature during the post-anthesis period (Ortiz-Monasterio et al. 1994).

6.6.2 Choice of Crops and Varieties

In the context of global climate change, C_4 crops should be preferred over C_3 crops because of less photorespiration and more photosynthetic efficiency. Instead of rice and wheat, maize should be preferred owing to its C_4 physiology (Edwards and Walker 1983). In crop simulation study using APSIM model, Dimes et al. (2008) concluded that sorghum and pigeon pea have better resilience to climate change as compared to maize and chickpea mainly due to improved harvest index and improved water use efficiency, respectively. Moreover, short-duration, high-temperature and drought-tolerant varieties should be preferred to increase the elasticity of the production system. Further, the choice of varieties can be narrowed based upon the specific situation. For instance, in low rainfall area, focus should be given on early maturing drought-tolerant varieties to avoid drought stress at sensitive crop growth stage, whereas the choice of long duration variety is judicious in case where moisture regimes exhibit little change. This is because warmer temperatures tend to speed up development and results in lower yields (Lobell and Burke 2008). Various crop model outputs have suggested that in the northern and southern parts of India where the detrimental effect of climate change is due to increased atmospheric temperature, farmers should go for heat-tolerant long duration variety which fit well in the period of available water. But in cooler region where the ill effect of climate change is due to increased atmospheric CO_2, farmers should grow crops and varieties having better harvest index. But under dryland conditions, where low moisture availability is the main problem and which is likely to be worsen further under climate change, it will be judicious to go for short duration crops having early maturity period. Cooper et al. (2009) simulated yield of long duration *Sorghum* variety (Brandes) through DSSAT model and suggested that it will mature in 119 days under present condition at Aurangabad but can mature only in 103 days under warmer climate change scenario (+3 °C temperature). They also predicted that this long duration variety can maintain its current production level even under warmer climate under present management practices. The rice cultivars which flower earlier maintain high number of spikelets per panicle when grown in warm environments (Singh et al. 2010). Similarly, in wheat, a positive correlation between grain yield and canopy temperature depression (CTD) has been reported and recommended as a useful trait for selecting high temperature-tolerant genotypes (Pradhan et al. 2012).

6.6.3 Change in Land Use

Reallocation of different crops based on the availability of bright sunshine hours and atmospheric temperature can offset the adverse effect of climate change. Parry et al. (1988) reported an “optimal land use” for Europe under climate change scenarios which increased the area cultivated with winter wheat, maize and vegetables, while allocation for spring wheat, barley and potato will be decreased. Rainfed areas of India have derived direct benefit by bringing more area under irrigation, high value crops and rehabilitation of degraded lands through watershed management programme (Wani et al. 2003, 2007). But we should be aware about the projections in areas where replacement of current land use pattern with some different crops and varieties may increase the vulnerability of that area to climate change. For example, Lorenzoni et al. (2001) projected that in the UK, there are certain areas where replacement of current land use under pastures with heat-tolerant crops like maize may increase the vulnerability of that areas to climate change leading to further worsening of the situation. But at the same time, there are researches to show that if the degraded fallow lands can be brought under afforestation with efficient species, it will help to increase the carbon stock of the agroecosystem which will help to decrease radiative forcing caused by anthropogenic factors. The list of some efficient agroforestry species is given below which can efficiently increase the carbon stock of the agroecosystem (Table 6.3).

Table 6.3 Soil organic carbon (SOC) stock of some agroforestry systems

Agroforestry systems/species	Location	Age	Soil depth (cm)	Soil C (Mgha^{-1})
Mixed stands (Eucalyptus + Casuarina (C), C + Leucaena (L), Eucalyptus + L)	Puerto Rico	4	0–40	61.9, 56.6 and 61.7
Agroforest [*Pseudotsuga menziesii* (Mirb.) Franco + *Trifolium subterraneum* L.]	Western Oregon, USA	11	0–45	95.9
Agrisilviculture (*Gmelina arborea* Roxb. + eight field crops)	Chhattisgarh, Central India	5	0–60	27.4
Tree-based intercropping: hybrid poplar + barley	Ontario, Canada	13	0–20	78.5
Silvopastoral system: *Acacia mangium* Willd. + *Arachis pintoi* Krapov. & W. C. Gregg	Pocora, Costa Rica	10–16	0–100	173
Alley cropping Leucaena – 4 m wide rows	Western Nigeria	5	0–10	13.6
Alley cropping: hybrid poplar + wheat, soybeans, and maize rotation	Southern Canada	13	0–40	125
Alley cropping: *Erythrina poeppigiana* (Walp.) O.F. Cook + maize & bean (*Phaseolus vulgaris* L.)	Costa Rica	19	0–40	162
Shaded coffee: *Coffea robusta* L. Linden + *Albizia* spp.	Southwestern Togo	13	0–40	97.3
Sivopasture: slash pine (*Pinus elliottii* Engelm.) + bahiagrass (*Paspalum notatum* Flugge)	Florida, USA	8–40	0–125	6.9−24.2
Home gardens: multipurpose trees (*Acacia mangium*) fruit/nut trees/latex yielding trees (arecanut, coconut, Tamarind, Sapota, etc.) and crops (banana, cassava, colocasia, black pepper, etc.)	Kerala, India	35+	0–100	101–126
Shaded cacao systems: cacao (*Theobroma cacao*) with Laurel (*Cordia alliodora*) or Poro (*Erythrina poeppigiana*)	Bahia, Brazil	30	0–100	302

Source: Adapted from Nair et al. (2010)

6.6.4 Irrigation and Nutrient Management

Under changing photothermal scenario due to climate change, it is expected that there will be a differential photosynthetic response of C_3 and C_4 crops. Though C_4 crops are more tolerant to heat and drought as expected due to climate change, they are less photosynthetically efficient under elevated CO_2 condition which is evident through positive radiative forcing projections in the coming decades. But, most C_4 species have their origin in warmer tropical region. So, under this situation C_4 species show higher photosynthetic efficiency and growth rates due to gains in water, carbon and nitrogen use efficiency. So, to meet up the increased demand of water and nutrients of C_4 crops, there is a need for effective management of irrigation and fertilization practices. The growth response of plants under elevated CO_2 is directly influenced by water and nutrient availability (Cambell and Sage 2002). It is also projected that the robust growth of crops under elevated CO_2 level demands more nitrogen.

Agustin (2006) reported that under positive radiative forcing due to elevated CO_2 concentration optimal planting dates with higher dose of nitrogen will increase the yield of maize by 14, 23 and 31% for 2020, 2050 and 2080,under SRES (Special Report on Emission Scenario)-A2 and 11, 15 and 21% under SRES-B2, respectively, over the same period. However, the supplemental irrigation strongly reverted the situation. They also reported the higher yield of soybean under higher nitrogen dose in both the emission scenarios.

There is a critical role of mineral nutrition to be played for enhancing the plant resistance to environmental stresses (Marschner 1995). Firstly, nitric oxide (NO) which is one of the nitrogen forms is highly reactive, and a broad spectrum of regulatory functions to pass free radical through semipermeable membrane is desirable in many physiological processes, viz. seed germination, leaf expansion, stomatal closure, ethylene emission, cell senescence and programmed cell death and a signal molecular mediating responses to biotic as well as abiotic stresses (Crawford and Guo 2005; Yang et al. 2006; Zhang et al. 2006; Zhao et al. 2007). Kato et al. (2003) reported that plants grown with higher nitrogen supply under high light intensity had greater tolerance to the damage caused by photo-oxidation and also enhances the photosynthetic capacity. The frost or chilling causes an oxidative damages which can be protected by providing higher dose of potassium to the plants (Waraich et al. 2011). Kafkafi (1990) reported that low temperature causes stem damage in carnation plants which can be protected by supplying higher dose of potassium in irrigation water to the plants. Hakerlerler et al. (1997) also reported that supply of potassium (depending on the source of potassium fertilizer) enhanced the total plant production in pepper (190%), eggplant (170%) and tomato (240%). Calcium has a very prominent role to maintain the cell structure and also plays a role as calmodulin which controls the plant metabolic activities, and under low temperature stress condition, enhancing plant growth (Waraich et al. 2011). The release of apoplastic or internal guard cell of Ca^{2+} partially mediated to ABA-induced stomatal closure (Wilkinson et al. 2001). Boron and magnesium stimulate the translocation of carbohydrates by enhancing phloem export and reducing ROS generation and damage due to photo-oxidation for maintaining the structure of chloroplast under high or low temperature conditions (Waraich et al. 2011). Under temperature stress condition, the enzymatic activities and antioxidant compounds are enhanced by manganese (Aktas et al. 2005; Turhan et al. 2006; Aloni et al. 2008). Djanaguiraman et al. (2005) reported that foliar spray of selenium decreases the ROS content and membrane damage where as increases the anti-oxidant enzyme activity in soybean.

6.6.5 Solar Radiation Management

The GHGs trap solar radiations and warm the Earth surface. The principal atmospheric gases like water vapour and clouds (36–72%), carbon dioxide (9–26%), methane (4–9%) and ozone (3–7%) participated in direct contribution to the greenhouse effect (Kiehl et al. 1997). To reduces these climate change effects, reduction in carbon intensity of the world through new low-carbon technologies and adopting them globally must be the priority. Solar radiation management proposals aim to reduce global warming by reducing the amount of light received on the Earth and by its atmosphere. It includes several techniques like space solar reflectors, stratospheric injection of aerosols, seeding tropospheric clouds by salt aerosols or ice nucleation to make them whiter and also surface albedo change (urban, rural or atmospheric approaches). When insufficient natural light is present in a greenhouse, LED lights are used to improve light conditions for optimizing phytochemical concentrations in vegetables (Samuoliene et al. 2012).

6.6.6 Managing GHGs Through Agricultural Adaptations

Agriculture contributes about half of the global emissions of two of the most potent non-carbon dioxide greenhouse gases: nitrous oxide and methane. The emissions of carbon dioxide from changes in agricultural land use can be reduced by slowing deforestation. The application of biochar with soil test-based balanced fertilizer enhanced the fertilizer use efficiency and reduced the prime greenhouse gas emission by increasing carbon sequestration. Other promising approaches are changes in agricultural land management (conservation tillage, intercropping/mixed cropping, agroforestry and rehabilitation of degraded crop and pasture land), overall improvement of nutrition and genetics of ruminant livestock, storage and capture technologies for manure and conversions of emissions into biogas. Some of these inventions have win-win outcomes in higher productivity, promotes better management of natural resources and production of valuable by-products, such as bioenergy. Others require substantial investment at the global level, such as the development of low-emission rice varieties and livestock breeds.

6.6.7 Biochemical and Molecular Tools Used to Mitigate Climate Change Effects on Crops

Sugarcane stubble buds may be protected from an oxidative damage by higher peroxidise and catalase activities, whereas accumulation of proline occurs to act as an osmoprotectant (Jain et al. 2007a, b). During freezing tolerance and cold acclimation, the confirmation for accumulation of proline is reported by several researchers (Paquin and Pelletier 1981; Koster and Lynch 1992; Dorffling et al. 1998). Under cold stress condition, higher level of acid invertase and reducing sugars were reported in sprouting of sugarcane buds during many studies (Jain and Madan 1999; Solomon et al. 1988; Solomon and Kumar 1987; Kanwar and Kaur

1977; Shrivastava et al. 2006). The lipid phase of the thylakoid membranes is photoprotected and stabilized by xanthophylls and terpenoids like isoprene or tocopherol (Velikova et al. 2005; Camejo et al. 2006). The thermotolerance in maize is induced by plant hormone ABA (Musatenko et al. 2003). Biosynthesis of major HSPs confers induction of high temperature stress tolerance in *Arabidopsis*, brassinosteroids and tomato (Ogweno et al. 2008; Bajguz and Hayat 2009). Similarly, higher HSPs synthesis and rapid continuation of protein synthesis due to heat stress epibrassinolide treatment which modulates the translational machinery in rapeseed and *Arabidopsis* under heat stress condition (Kagale et al. 2007).

To protect from heat stress condition, late embryogenesis abundant (LEA) proteins, dehydrins and ubiquitin have found to play imperative roles (Willits and Peet 1998). To understand tolerance mechanism is one way to detect adaptive QTLs for high temperature tolerance. Genetic markers related to different environmental stress conditions have already identified several studies (Roy et al. 2011). The revealing of genetic basis for plant stress tolerance in some crops has led to the release of plants with enhanced tolerance to abiotic stress condition, in which marker-assisted selection approaches have significantly contributed its key role (Lopes and Reynolds 2010; Thomson et al. 2010).

6.7 Steps Involved in Management Strategies

The application of technologies is likely to be a more successive process rather than an on and off activity. After modification of some steps, Stalker (2006) suggested the four main steps to be followed for implementation of the technologies successively (Fig. 6.2).

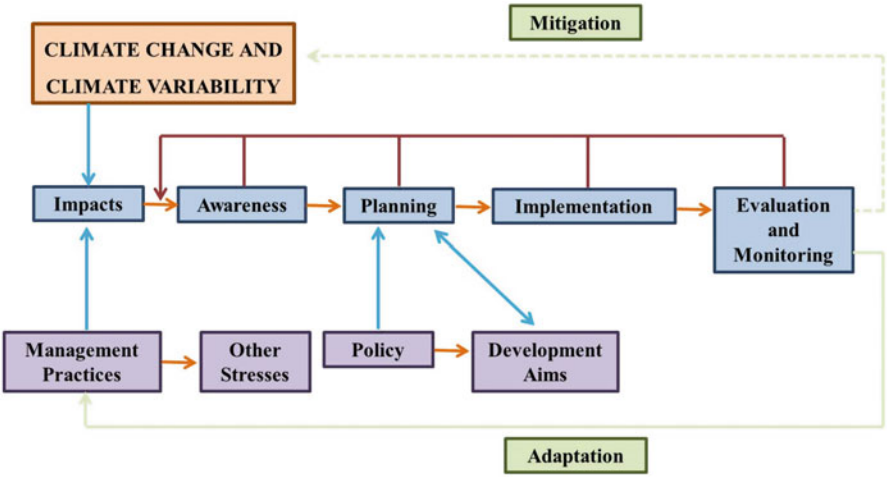

Fig. 6.2 Steps in planned adaptation to cope with changing photothermal environment resulting from climate change (modified from Stalker 2006)

6.8 Way Forward

Photothermal environment of the atmosphere is changing gradually due to several anthropogenic and natural causes as evidenced from their respective contributory positive radiative forcing values. This situation can be managed in a better way through climate resilient diversified crop production and land use systems. In this regard, few potential, farmer-friendly options are sowing a thermo-sensitive crop like wheat at a time which can ensure a congenial exposure of higher solar radiation and lower atmospheric temperature and by preferring high temperature tolerant and lower water demanding crops like maize, sorghum (C_4 cereals) etc. which are at the same time photosynthetically more efficient. Likewise, short duration hardy pulses like horse gram, kidney bean, black gram etc. can be promoted instead of chickpea and lentil. Sowing climate resilient varieties of these crops is also a noble option for tackling the situation. Using higher dose of fertilizer and giving frequent light irrigation can also be thought as some procedure in harnessing a good yield in the changing photothermal scenario. Moreover, increasing carbon stock in the soil through region-specific suitable agroforestry systems can reduce the positive values of radiative forcing and make the photothermal environment more favourable for crop production. The use of some molecular and biological tools helps for increasing crop tolerance. Genetic research and screens can also be used to explore the loci and pathways that underlie these environmental sensitivities. None of these options will work alone. It is highly required to integrate all these options based on local and regional requirements and availability of resources. Management strategies such as crop rotation, land use planning, use of improved crop varieties, managing sowing date and integrated nutrient and water management are expected to help minimize the risk associated with yield variability under future climatic conditions.

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Heat Stress in Field Crops: Impact and Management Approaches

7

S. S. Sandhu, Jagdish Singh, Prabhjyot Kaur, and K. K. Gill

Abstract

The concentration of greenhouse gases has been increasing year by year leading to global warming. The concentrations of CO_2 and other greenhouse gases may rise up to 500–1000 ppm by the end of this century that can trap heat radiated from the earth leading to an increase in global mean temperature by 1–3 °C. The increasing temperature will affect the crop production by affecting the duration and phenology of crop, distribution pattern of a particular crop, etc. In this chapter the studies on the impact of heat stress on plant growth, development, and yield and various options to escape or tolerate heat stress have been reviewed. The various agronomic options discussed include selection of cultivar, sowing date, sowing method, and irrigation scheduling. The chemicals available for mitigating the effect of heat stress are osmoprotectants (proline), phytohormones (salicylic acid, abscisic acid), signaling molecules (nitric oxide), trace elements (calcium), and plant nutrients (N, P, K, Bo, Zn, etc.).

Keywords

Heat Stress · Wheat · Rice · Temperature · Management · Physiology · Phenology

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7.1 Introduction

The concentrations of atmospheric carbon dioxide (CO_2) has been rising consistently, from 315 ppm (1959) to 385 ppm (2008), 392.6 ppm (2014), and 403.95 ppm (July 2017) (Keeling et al. 2009, IPCC 2014 and ESRL 2017) (Fig. 7.1). Current projections showed that by the end of this century, the concentrations of CO_2 will continue to rise and may reach 500–1000 ppm (IPCC 2007a). The global mean temperature has increased due to increase in concentration of greenhouse gases (GHG) as they trap heat radiated from the earth. The mean global temperature may rise by 0.3 °C per decade (Jones et al. 1999) with an uncertainty of 0.2–0.5% (Houghton et al. 1990) and would rise higher by 1 °C and 3 °C above the present temperature by the years 2025 and 2100, respectively, ultimately causing global warming. This higher temperature may alter distribution and growing season of crops by affecting the threshold temperatures for life processes (Porter 2005). Worldwide, high ambient temperature is regarded as a serious threat to crop production (Bal and Minhas 2017; Hall 2001; Lobell and Asner 2003).

High temperature stress or heat stress may be defined as the period in which ambient air temperature remains high for a sufficient period to harm the plant functions and/or its development in an irreversible manner. Plants can be damaged by either high day or high night temperatures or by either high air or soil temperatures. Fischer and Byerlee (1991) defined continuous high temperature stress for wheat as when the mean average temperature of the coolest month is greater than 17.5 °C. The temperatures range of 30–40 °C can be termed as moderately high temperatures for some plant species in which such high temperatures can cause reversible inhibition of metabolism (moderate heat stress). The temperature of plant usually remains just above the air temperature. The threshold temperature refers to a

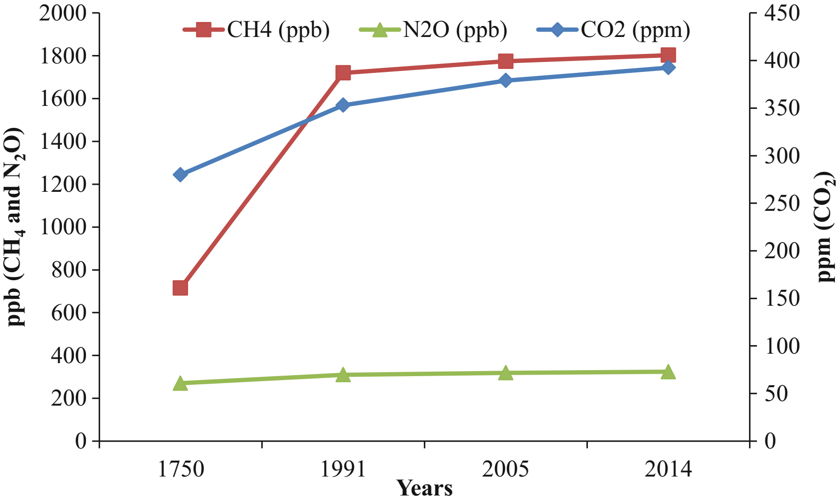

Fig. 7.1 Change in major greenhouse gases

value of daily mean temperature at which reduction in growth is detectable. The information of threshold temperatures is important in research on crop physiology and production. The base threshold temperatures may vary with plant species.

Worldwide, crop production is limited by high temperature stress. In the tropical and subtropical climates, the high temperature sensitivity is more important and is becoming the major limiting factor for production of field crops. Almost 90% of the water that enters a plant system is used for cooling itself under warm conditions. The important weather parameters like temperature, humidity, intensity, and duration of light and speed of wind influence the quantity of water lost by plant for its cooling. During grain filling stage, if the plants are exposed to high temperature, it can accelerate senescence and reduce the individual grain weight and ultimately productivity (Siddique et al. 1999). It is also predicted that the crops may experience more thermal stresses in the coming times, due to predicted temperature increase of about 2 °C by the middle of twenty-first century (Karttenberg et al. 1995).

7.2 Extent of Damage

The damage due to high temperature stress is serious when it occur parallel to the reproductive period. According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the global food supply is threatened by heat stress (IPCC 2007b). The extent of damage from heat stress is determined by the environmental factors like intensity, duration, and rate of change in temperature and plant factors like its stage of development and growing conditions before exposure to high temperature.

At global level wheat, maize, and barley productivity responded negatively to rising temperature during 1981–2002, costing an estimated loss of $5 billion per year (Lobell and Field 2007). In the United States, during the period of 1976 to 2006, the northern corn belt was adversely affected by rising temperatures during growing season of maize and soybean; as a result their production was affected (Kucharik and Serbin 2008). In the IPCC scenario with the slowest warming trend, it has been predicted that maize and soybean yield would decrease by 30–46% before the end of the century (Schlenker and Roberts 2009). In the year 2003, Europe experienced a heat wave in the month of July, where temperatures rose by 6 °C above average and annual precipitation was below average by 50% and resulted in record crop yield reduction (Ciais et al. 2005). During March 2004, Indo-Gangetic Plains in India experienced higher temperatures by 3–6 °C which advanced the crop maturity by10–20 days and accompanied by four million tonnes reduction in wheat production (Aggarwal 2008). During 2008–2009 wheat experienced heat stress in Ludhiana district of Punjab (India) which reduced the productivity to 4.4 t ha^{-1}, whereas the average productivity during the years having normal temperature was 4.8 t ha^{-1}. An increase of 2 °C in temperature from normal reduced the potential grain yield of wheat at most of the places in India (Aggarwal and Sinha 1993). A field experiment was conducted at Ludhiana during 2013–2014 on wheat by artificially increasing (3 °C higher than ambient) temperature (heat stress) inside the small polyhouses. It

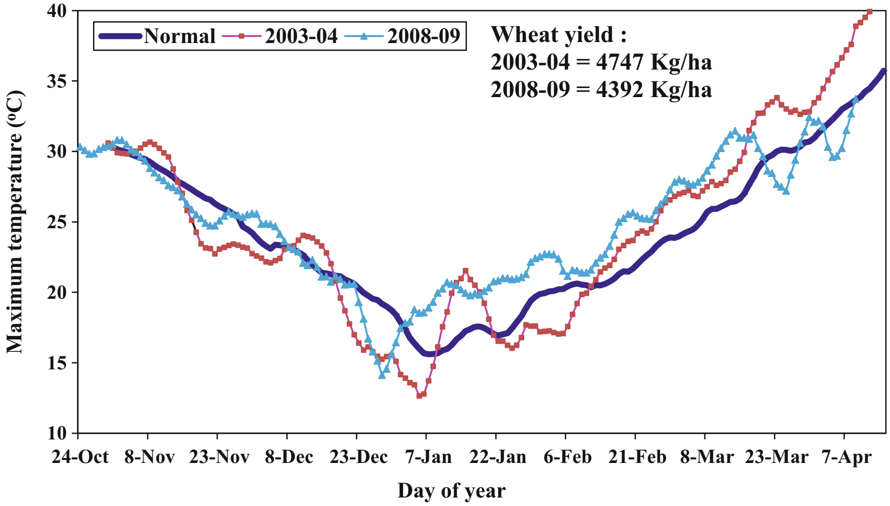

Fig. 7.2 Maximum temperature (7-day moving average) at Ludhiana during heat wave crop years

was observed that the temperature increase during first week of February caused the grain yield reduction by 3.2%. In the second and third week, the decrease was 12.8 and 20.1%, respectively, as compared to yield obtained under ambient temperature conditions (Anonymous 2014a).

Bal et al. (2004) reported significant association between various weather parameters including maximum and minimum temperature on the long-term wheat productivity at Ludhiana Punjab after removing the increase in productivity due to technological upgrade factor. An experiment on rice was conducted at Ludhiana, India during 2013 in which heat stress (3 °C higher than ambient) was applied by placing the pots inside the polyhouse. The reduction (31.7%) in grain yield was maximum if heat stress was applied at anthesis, and it was 17.3% in heat stress during grain development stage (Anonymous 2014b).

The temperature variation during 2 heat wave and 2 cold wave years at Ludhiana is presented in Figs. 7.2, 7.3, 7.4, and 7.5. Maximum temperature during 2003–2004 (Fig. 7.2) remained higher during some days in November and December and then continuously higher than normal after mid-February. While, in the year 2008–2009, the maximum temperature remained higher than normal during the end November to first week of December and later on continuously higher during January to April. Similarly, the minimum temperature (Fig. 7.3) remained higher than normal for most of the time during the crop growth period during the 2 years (2003–2004 and 2008–2009) that resulted in a reduced crop yield of 4747 and 4392 kg/ha during these years, respectively.

The temperature variation during 2 cold wave years at Ludhiana is presented in Figs. 7.4 and 7.5. Maximum temperature during 2010–2011 (Fig. 7.4) remained near normal during November and December, considerably lower during the first few

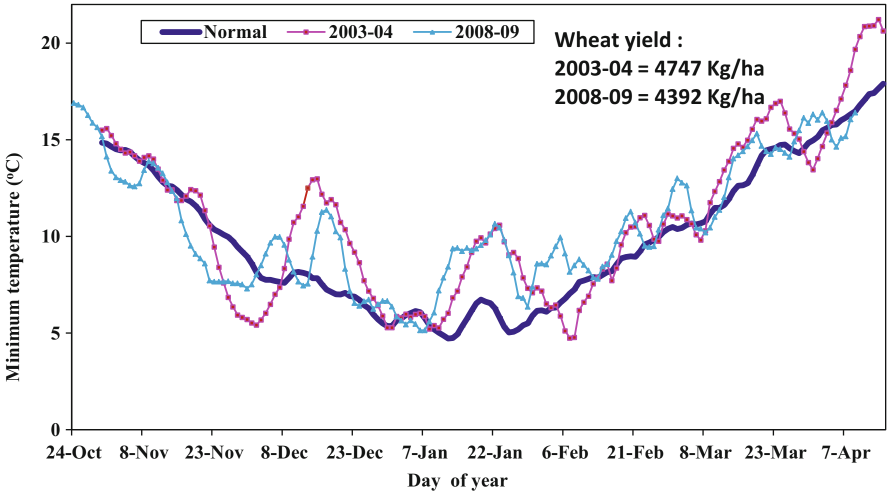

Fig. 7.3 Minimum temperature (7-day moving average) at Ludhiana during heat wave crop years

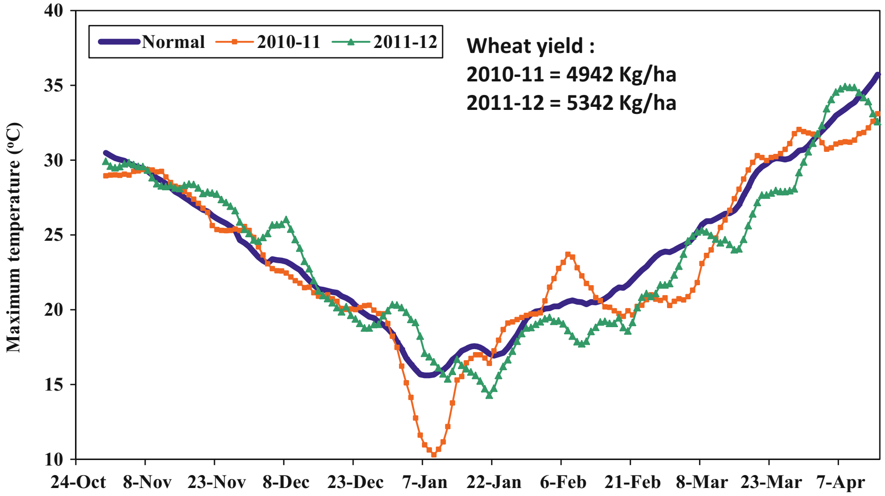

Fig. 7.4 Maximum temperature (7-day moving average) at Ludhiana during cold wave crop years

days of January and during mid-February to mid-March and then during start of April. While during the year 2011–2012, maximum temperature continuously remained lower than normal during mid-January to end of March, while minimum temperature remained lower than normal during mid-January to start of February and during end February to mid-March. However, during 2011–2012, minimum temperature remained lower than normal during mid-December to the first week of January and then contentiously lower from end of January to end of March except for

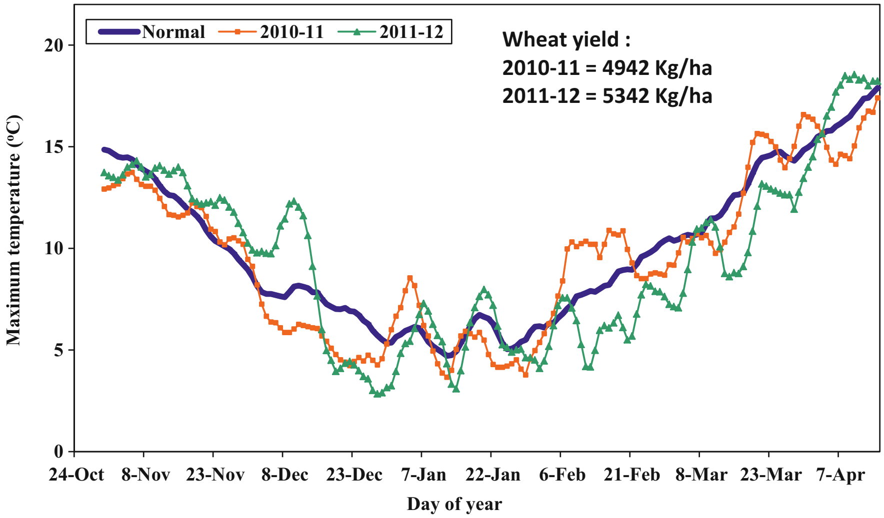

Fig. 7.5 Minimum temperature (7-day moving average) at Ludhiana during cold wave crop years

few day when it was higher than normal. These lower temperatures resulted in higher productivity of 4942 and 5342 kg/ha during 2010–2011 and 2011–2012, respectively.

7.3 Plant's Defense Mechanism Against Heat Stress

The plants reduces the quantity of incident radiation absorbed by increasing the reflectance of its surface by the means of leaf hairs and scales, which scatter the incident radiation, thus reducing the energy available over the leaf surface. Some plants deposit a layer of wax on the epidermis that increases reflectance in addition to reducing water loss. Plants have various mechanisms for surviving under heat stress such as long-term evolutionary adaptations in phenological and morphological characters and short-term avoidance or acclimation mechanisms like adjusting leaf orientation, cooling through transpiration, or change in lipid compositions of membranes. Srivastava et al. (2012) observed closure of stomata, increased stomatal and trichomatous densities, and larger xylem vessels when plant was exposed to heat. Plants regulate their energy budget to escape excessive heat. The plant reduces quantity of solar radiation intercepted through specialized leaf and canopy arrangements. In case of eucalyptus, it rearranges its leaves vertically and canopy architecture so as to minimize the canopy exposure to direct sun. Some plants reduce heat load by moving, rolling, and/or adjusting orientation of leaves so that the leaf surfaces are not perpendicular to the sun rays and leaf moments are commonly observed in legumes (Angus et al. 2010).

The another mechanism adapted by plant species is production of smaller leaves that increases heat loss as the divided leaves decrease the boundary layer resistance thereby increasing convective cooling as well as transpiration. The leaf also losses heat by transpiration of water molecules from its surface also termed as transpiration cooling. Transpiration cooling can reduce leaf temperatures to 5 °C below ambient air temperature. In cultivated crops, high temperatures and water deficit, generally does not occur simultaneously. Therefore, the cultivars having high stomatal conductance are found to be more resistant to high temperature (Angus et al. 2010). The ability of plants to withstand extreme temperatures is mainly determined by environmental and genetic factors. The stability of life processes mostly ranges from some degrees above zero to around 35 °C (Zróbek-sokolnik 2012).

7.4 Effects of Heat Stress

7.4.1 Effect of Heat Stress on Plant Physiology

Photosynthesis depends on the ability of the crop canopy to intercept light, duration of light capture, photosynthetic capacity, and efficiency of the canopy. Photosynthesis is less sensitive to temperature increase as compared to respiration process and has the similar declining pattern as that of respiration. Xu et al. (1995) found that due to heat stress, structure and function of chloroplasts get disrupted and chlorophyll content reduced which ultimately reduces photosynthesis. Respiration increases rapidly with temperature and drops significantly at further higher temperature. Heat stress induces changes in photosynthesis and respiration which results in shortening of life cycle and reduced plant productivity (Barnabas et al. 2008). With every 10 °C rise in temperature, the average rate of enzymatic reactions increases twofold within the range up to 50 °C. The enzymes are permanently denatured and inactivated if temperatures rise above 60 °C except in thermopiles. The critical or lethal temperature is unique for each life process when it rises above that particularly it causes irreversible damage to cell structures and may result in death of the plant (Zróbek-sokolnik 2012).

Prasad et al. (2011) reported that chlorophyll content of wheat and its photosynthetic rate decreased by 8 and 22%, respectively, due to high nighttime temperature (31.9 °C/27.8 °C) as compared to optimum nighttime temperature. Almeselmani et al. (2012) observed that the leaf chlorophyll content of wheat cultivar PBW 343 and C306 was significantly reduced by high temperature (35/25 °C day/night) at any stages of growth. The leaf chlorophyll content of wheat cultivar C306 was reduced at anthesis and 15 days after anthesis by 23 and 48%, respectively, while in PBW343, corresponding reduction was 29 and 61%. Shah and Paulsen (2003) reported that during reproductive stage of wheat, if temperature increases it will result in enhanced rate of decline of photosynthesis and leaf area coupled with decreases in shoot and grain mass, sugar content of grains, and water-use efficiency.

Table 7.1 Ranges of temperature for seed germination of different crops (Hasanuzzaman et al. 2013)

Crop	Temperature (°C)		
	Minimum	Maximum	Optimum
Rice	10	45	20–35
Wheat	20	40	25–30
Maize	10	40	25–30
Soybean	10	35	25–30
Tomato	11	30	15–27
Cucumber	18	30	25–30
Peeper	15	35	20–30
Carrot	11	30	15–25
Cabbage	8	35	15–30

7.4.2 Effect of Heat Stress on Seed Germination

Good seed germination is one of the key requirements to get good and uniform crop stand and subsequently high yield of the crop. The germination of seeds is dependent on soil temperature, soil moisture, and soil aeration. The temperature ranges for germination of various crops have been given in the Table 7.1. The temperature affects the seed germination of plants by determining the rate of deterioration of seed, rate of loss of dormancy, and the rate of germination (Roberts 1988).

Prasad et al. (2006) found that the increase in seed-zone temperature between base temperature and optimum temperature resulted in increased germination rate; however, further rise in seed-zone temperature above optimum or maximum threshold temperature resulted in reduction in seed germination. Essemine et al. (2010) observed that the rate of germination of wheat was not optimum under very high temperature (45 °C) due to death of cells and damage to embryo during the early stage of crop development, indicating that the temperature above 45 °C did not allow establishment of new seedlings. Essemine et al. (2010) further reported that wheat plants grown under high temperature produced low-quality seeds having poor germination rate and vigor. Reduction in germination rate, plant emergence, poor vigor of seedling, abnormal seedlings, reduced radicle, and plumule growth in geminated seedlings due to heat stress have been reported in many plant species (Toh et al. 2008; Essemine et al. 2010; Piramila et al. 2012).

7.4.3 Effect of Heat Stress on Growth and Development

The most important effect of heat stress on plants is the reduction in the growth rate; however, coupled effect of heat and drought stress has more detrimental effects on growth and productivity of crops as compared to the effect of the individual stress (Prasad et al. 2008). The exposure of plant to heat stress significantly affects cell division and elongation rates that affect the size of leaf and dry matter yield of the plants. Ahamed et al. (2010) reported that a number of tillers and plant height of four different genotypes of wheat were negatively affected due to heat stress. Al-Busaidi et al. (2012) observed that the exposure of high atmospheric temperature resulted in the significant water loss that negatively affected the growth and dry matter production in *Jatropha curcas*. Wahid (2007) documented that high temperature exposure of sugarcane plants will decrease shoot dry weight, net assimilation rate (NAR), and relative growth rate (RGR). Wahid (2007) observed that exposure of plants to high temperature stress resulted in reduced cell size and closure of stomata resulting in reduced water loss, increased stomatal and trichomatous densities, and increased size of xylem vessels in stem and roots. Wahid et al. (2007) highlighted that the pre- and postharvest damages as a result of high temperature can be due to scorching of leaves and twigs, sun burning of leaves, branches and stems, leaf senescence and abscission, inhibition of shoot and root growth, fruit discoloration, and damage. Johkan et al. (2011) found that the exposure of wheat plant to the high nighttime temperature resulted in decrease in number of tillers but enhanced shoot elongation. Schöffl et al. (1999) reported that high temperature negatively affects plants and results in severe injury at cellular level that was attributed to collapse of cellular organization, ultimately leading to death of cell. Zhang et al. (2009) concluded that the heat-tolerant rice cultivar has flag leaves with tightly packed mesophyll cells, well-developed vascular bundles, and a few closed stomata, while heat-sensitive rice cultivar lacked such features.

The plant growth rate increases with rise in temperature up to a certain point and then starts declining with further rise in temperature. The respiration activities increase up to some extent with rise in temperature and thereafter decline with further increase in temperature. Respiration rate increases with increase in growth rate and declines with decline in growth rate. The photosynthesis process is relatively less sensitive to temperature as compared to respiration process; however, the declining trend in photosynthesis process is like respiration (Fitter and Hay 2002).

7.4.4 Effect of Heat Stress on Fertilization

Sakata and Higashitani (2008) and Wassmann et al. (2009) reported that male sterility and impairment of pollen development as a result of heat stress are the main reasons for reduced yield. The yield reduction in response to elevated temperatures due to low pollen viability and germination was observed by many researches (Gross and Kigel 1994; Sato et al. 2000; Prasad et al. 2001; Kozai et al. 2004). In *Phaseolus vulgaris* heat stress at pre-anthesis stage resulted in abnormalities in pollen and anther development (Porch and Jahn 2001). Peng et al. (2004) observed that high night temperature causes reduction in rice yield and also figured that a number of fertile spikelets in rice and nighttime temperatures have a strong negative linear relationship.

7.4.5 Effect of Heat Stress on Dry Matter Production and Yield

The exposure of plant to high temperature negatively affects establishment, growth, dry matter partitioning, photosynthesis, and reproductive growth and ultimately affects the crop yield. The reduction in crop yield as a result of exposure to high temperature varies with the duration of exposure; degree of heat and crop genotype has been reported by several authors (Rahman et al. 2009; Islam 2011; Lin et al. 2010; Mohammed and Tarpley 2010; Kim and Lee 2011; Prasad et al. 2011). In *Brassica* oilseeds, Mendham and Salsbury (1995) found that the reduction in crop yield in response to high temperature was due to disturbance of relationship of source and sink for assimilation of photosynthates. Djanaguiraman et al. (2010) compared the yield attributes and yield of sorghum plants grown under normal (32/22 °C) and high temperature (40/30 °C) and concluded significant yield reduction in plants exposed to high temperature as compared to plants grown under normal temperature. The plants exposed to high temperature for 45 days showed a reduction of 22, 14, 53, and 36% in plant height, leaf dry weight, grain weight, and total dry weight, respectively. Monjardino et al. (2005) observed impaired endosperm cell division and development and reduced grain yield in maize due to high temperature. Altenbach et al. (2003) found that the high temperature shortened the duration of grain filling and decreased the time for apoptosis and maturity resulting in yield reduction. Morita et al. (2005) observed reduction in grain length and width of cereals due to reduction in the average area of endosperm cells in response to high nighttime temperature. Zakaria et al. (2002) concluded that due to high temperature, rate of kernel development increases and duration of dry matter accumulation decrease. Prasad et al. (2006) mentioned 10 and 99% reduction in seed yield of sorghum when temperature increased from 32/22 °C to 36/26 °C and 40/30 °C, respectively. Johkan et al. (2011) observed reduced yield in *T. aestivum* due to immature grains because of dark respiration under high temperature.

7.5 Heat Stress in Wheat

Globally, wheat is grown on an area of about 221.70 million hectares in a wide range of environment, with an annual production of about 655.80 million tonnes. India is the second largest wheat-producing nation with area of 30.23 million hectares and production of 93.50 million tonnes and average yield of 3.09 tonnes per hectare during 2015–2016. Wheat is the most sensitive crop to high temperature, at the reproductive growth, especially during grain filling. The heat stress in wheat focusing on the period of grain filling has been extensively studied by several workers (Borghi et al. 1995; Corbellini et al. 1997; Corbellini et al. 1998; Stone and Nicolas 1998) and concluded two typical heat stresses during the wheat grain filling, i.e., heat shock and chronic heat stress. “Heat shock” is characterized by sudden, extremely high temperatures (>32 °C) for a shorter duration (3–5 days), while “chronic heat stress” is characterized by moderately high maximum temperatures (20–30 °C) for a longer duration. Sharma (2000) reported that the best temperature regime for optimum growth and yield of wheat crop is 20–22 °C at sowing, 16–22 °C at tilling to grain filling, and slow rise of temperature to 40 °C at harvesting. However, Farooq et al. (2011) reported that the optimum temperature for wheat at anthesis and grain filling ranges from 12 to 22 °C. An average optimum temperature of 15 °C for grain filling stage is also reported by Chowdhary and Wardlaw (1978). The important constraint to wheat production is the occurrence of high temperatures during kernel development (Rane et al. 2000) which drastically reduces the grain filling period, particularly under late sown conditions (Sharma 1992). Harrison et al. (2000) reported that high temperature during November sown wheat accelerates its growth resulting in earlier jointing stage which reduces tillering period. Studies (Blum et al. 2001; Laghari et al. 2012) had reported that exposure to heat stress in wheat crop accelerates the development stages to such a degree that necessary supply of environmental inputs (radiation, water, and nutrient) is not met. Ford et al. (1975) found that heat stress after flowering accelerates leaf senescence, thus reducing grain filling stage resulting in grain yield reduction.

Almeselmani et al. (2012) found negative effect of high temperature (35 °C) on chlorophyll content, net photosynthesis, and RuBisCO activity in wheat. Demirevska-Kepova et al. (2005) also observed adverse effect of high temperature (40 °C) on chlorophyll content of wheat, while Law and Crafts-Brandner (1999) reported that high temperature (45 °C) in wheat could significantly reduce net photosynthesis and increase respiration.

Exposure to above optimum temperatures can significantly reduce productivity (Macas et al. 2000; Tewolde et al. 2006). Some studies (Gibson and Paulsen 1999; Mian et al. 2007) have reported that average daily temperature above 15 °C during grain filling period caused a reduction in grain yield. Dias and Lidon (2009) concluded that high temperature during grain filling increases the rate of grain filling but shortened its duration. Yin et al. (2009) observed that the grain filling duration was shortened by 12 days in wheat crop with 5 °C increase in temperature above 20 °C which led to an increase in rate of grain filling and reduced the grain yield.

The temperature sensitivity of wheat at different growth stages (Table 7.2) was reported by Slafer and Rawson (1994). Heat stress at anthesis stage increases floret abortion (Wardlaw and Wrigley 1994). Saini and Aspinall (1982) reported that in wheat, at floret formation stage, temperatures above 30 °C may cause complete sterility. Heat stress during the reproductive stage resulted in pollen sterility, tissue dehydration, and increased photorespiration. However, high temperatures increase

Table 7.2 Temperature sensitivity of different phenological stages of wheat

Phenological stages	Sensitivity to temperature
Germination	High
Jointing	High
Tillering	High
Spikelet production	Low to moderate
Spikelet development	Moderate to high
Grain filling	Moderate to high
Grain development	Moderate to high

growth (Kase and Catsky 1984), but also reduce the period between successive phonological events, that can never be compensated by the increased growth rate (Zahedi and Jenner 2003). Mohammadi et al. (2012) observed that high temperature reduces time duration between heading and maturity of wheat. The grain filling duration was adversely affected in heated environment. Thousand-kernel weight was highly correlated with canopy temperature in dry land and heat conditions but not in supplemental irrigation environment. They further concluded that the combined heat and drought stress reduced grain yield more than by either stress alone, but not with additive effects.

High temperature affects the grain yield and quality of wheat by affecting its sink strength and source capacity. Rane et al. (2007) reported that delay in sowing of wheat causes reduction in biological yield due to decrease in duration of life cycle as a result of occurrence of terminal heat stress. Moshatati et al. (2012) conducted an experiment in Iran and found that by sowing wheat beyond the optimum window, the crop experiences high temperatures during grain filling period, consequently there occurs a reduction in yield components and grain yield. Several studies (Gibson and Paulsen 1999; Ayeneh et al. 2002; Irfaq et al. 2005) reported that heat stress causes a reduction in crop stand, duration of life cycle, number of tillers, crop biomass, fertilization and grain development, size of ear, number of spikes per ear, and grain yield. Prasad et al. (2011) reported that the spring wheat plants grown under high temperature (31/18 °C) showed reduction of 50, 20, and 39% in a number of grains per spike, dry weight, and grain yield, respectively, as compared to that under optimum temperature (24/14 °C). Prasad et al. (2008) highlighted that high temperature stress in late sown wheat resulted in reduced ear length, number of spikelet per main stem, and number of fertile floret per main stem $^{-1}$ which ultimately caused a reduction in grain yield. Rahman et al. (2009) exposed wheat to 37/28 °C (day/night) temperature for 20 days at grain filling and maturity stage and found shortened grain filling duration and maturity period and reduced kernel weight and finally reduction in grain yield. The exposure of wheat to 30/25 °C day/night temperature from 60 DAS up to maturity resulted in reduction of leaf size, days to booting, heading, anthesis and maturity, severe reduction of number of grains/spike and reduced grain size, and ultimately productivity (Djanaguiraman et al. 2010). Under heat stress conditions, the supply of photo-assimilates is limited (Calderini et al. 2006) that resulted in poor yield. Streck (2005) found that in wheat, an increase of every 1°C beyond a temperature of 15–20 °C reduces the duration of grain filling by 2.8 days. Parry and Swaminathan (1992) observed that an increase of 0.5 °C temperature caused a reduction in duration of crop by 7 days along with a yield reduction of 0.5 t ha^{-1} in North India. Sandhu et al. (2016) concluded from a crop growth simulation modeling study that in central Punjab of India, the same level of heat stress can have different effects on wheat sown on different dates and the same level of heat stress can have positive and negative effects on wheat productivity, but the nature and quantum of effect varies with the timing of the heat stress.

7.6 Heat Stress in Rice

Rice (*Oryza sativa* L.), with global production of more than 740 million tonnes during 2016 (FAOSTAT 2018), is the staple food for nearly half the world population (Singh and Singh 2017). Development of male gametophyte in rice is extremely susceptible to high temperature, which directly cause grain yield reduction. Zakaria et al. (2002) found that the spikelet fertility of rice was highly sensitive to temperature during night, while degree of sensitivity to nighttime temperature was dependent on the developmental stage of the spikelet. Satake and Yoshida (1978) and Farrell et al. (2006) found that the most susceptible stages to high temperature stress in rice are anthesis, fertilization, and to some extent microsporogenesis (booting). The strong negative linear relationship between increase in nighttime temperatures and the number of fertile spikelets was observed by Peng et al. (2004). Morita et al. (2005) reported a reduction in the average area of endosperm cells in response to high nighttime temperature. Yoshida et al. (1981) observed reduced spikelet fertility in rice due to exposure to night temperature higher than 30 °C. Rice productivity is affected due to altered pollen germination and spikelet fertility as a result of high nighttime temperature (Mohammed and Tarpley 2009).

The higher nighttime temperature increases canopy respiration that negatively affects grain yield (Streck 2005). Sujatha et al. (2008) found that the decrease in photosynthetic rate was linked to the reduction in sucrose-P-synthase (SPS) activity under high temperature stress in rice. Scafaro et al. (2010) reported negative effect of high temperature (45 °C) on the Ferredoxin-NADP(H) oxidoreductase thiamine concentration in rice plants. Mohammed and Tarpley (2010) observed that the rice crop exposed to 32 °C temperature during night at reproductive stage resulted in increased spikelet sterility; decreased grain size, viz., length, width, and weight; and ultimately reduced yield. Rice plant grown under 25–42.5 °C temperature at vegetative growth stage resulted in decrease in the carbon dioxide assimilation rate.

Seshu and Cady (1984) observed that rice yield reduces by 41 gm^{-2} with an increase in average minimum temperature by 1.0 °C from 22 to 23 °C. Kanno and Makino (2010) reported that in rice during the vegetative stage, if night temperature increases up to 27 °C, it causes an increase in specific leaf area, leaf area, and leaf weight ratio; however, cool night temperature increases the grain yield and biomass. Peng et al. (2004) observed a decrease in grain yield of rice up to 10% with an increase in minimum temperature by 1 °C, and the reduction in grain yield was mainly due to the decrease in number of spikelets per plant. Welch et al. (2010) concluded from a database obtained from 227 intensively managed irrigated rice farms spread over 6 important rice-producing countries that higher minimum temperature reduces, while higher maximum temperature increases the grain yield.

7.7 Mitigating the Impact of Heat Stress

7.7.1 Agronomic/Crop Management Options

High temperature stress could be avoided by agronomic/crop management practices discussed below.

7.7.1.1 Selection of Proper Tillage/Sowing Methods

The selection of type of tillage and planting methods plays an important role in emergence and crop growth. However, the sowing of crop using different tillage options mostly depends on soil type, sowing time, water availability, etc. The methods of planting may affect the plants tolerance against heat stress through the soil moisture. The presence of crop residues/mulch on the soil surface protects the crop from high temperature during its initial growth period and keeps soil temperature lower than ambient during the day and higher at night and also conserves soil moisture (Geiger et al. 1992). The availability of optimum soil moisture increases transpiration process thereby reducing the canopy temperature and thus may protect the crop from probable yield decline by overcoming the heat stress. The tillage options such as zero tillage, bed planting, and conventional tillage with residue mulching produce higher grain yield and may help in mitigating the adverse impacts of high temperature during growth period of a crop.

7.7.1.2 Choice of Sowing Date and Cultivars

The selection of cultivar with respect to date of sowing and expected temperature rise during the crop growth period is important to get a better yield under high temperature stress conditions. In wheat, periods of elevated temperature may or may not occur during the growing season of the crop, but during grain filling, seasonal temperatures are mostly increasing. Loss and Siddique (1994) indicated that early planting of wheat may coincide grain filling with cooler temperatures thus avoiding terminal heat stress and leading to better yield. Gouachea et al. (2012) explored the effects of different agronomic practices such as earlier sowing, use of earlier maturing cultivars, and heat stress-tolerant cultivars using simulation approaches in France. The results showed earlier sowing dates were less efficient in yield enhancement as compared to earlier heading cultivars. As per the Directorate of Wheat Research Perspective Plan Vision-2025, varieties like PBW-373 and Kaushambi (HW-2045) possess terminal heat stress tolerance, and Naina (K-9533) and Parbhani-51 are heat-tolerant varieties which can overcome the adverse effect of heat stress on wheat crop. Selecting optimum sowing time helps in avoiding high temperature stress during anthesis and grain filling; thus crop escapes from hot and desiccating wind during grain filling period.

7.7.1.3 Water Management

Water management is critical from the point of view of damage due to high temperature stress, as high temperature is mostly associated with water stress. Plants can tolerate heat stress until crop can transpire freely. Continuous supply of water to heat-stressed crop may help sustain grain filling rate, duration, and size of grain (Dupont et al. 2006). Irrigation scheduling, according to critical stages of crop growth, soil type, and prevailing environmental conditions, helps the crop in mitigating high temperature stress and achieving optimum growth. Irrigation of wheat crop at the time of grain filling was found beneficial if temperature rose during that period (PAU 2015). Water-stressed plants close their stomata in order to conserve water; as a result cooling due to transpiration diminishes, and leaf temperatures might increase to lethal levels resulting in breakdown of plant processes. Proper irrigation methods based on soil type and availability of irrigation water and irrigation scheduling according to growth stages and weather may help in mitigating the effects of heat stress on crop. Supply of sufficient water can help in withstanding the air temperatures of 40 °C in field crops otherwise if water is limiting, 40 °C may kill the leaves (CIMMYT 2018).

7.7.2 Applications of Protectants/Chemicals/Nutrients

Certain chemicals may protect the plants against ill effects of high temperature. Literature available on the effect and use of such chemicals is being summarized in the following sections.

7.7.2.1 Osmoprotectants

Proline is membrane protectant, with low-molecular weight, and helps in maintaining the structure of enzymes and proteins, membrane integrity, and scavenges reactive oxygen species (Hameed et al. 2012). Under stress conditions proline accumulates in high concentrations in the cell cytoplasm without interfering with cellular structure and metabolism. Rasheed et al. (2011) applied exogenous proline (20 mm) to sugarcane nodal buds and observed desirable changes in anatomical and physiological parameters leading to mitigation of the adverse effects of heat stress. The application of proline considerably reduces the hydrogen peroxide production, improves the accumulation of soluble sugars, and protects the developing tissues from high temperature stress. Kaushal et al. (2011) observed that exogenous proline provides the protection to important enzymes of antioxidant and carbon metabolism thus providing tolerance in chickpea (*Cicer arietinum* L.) to heat stress. They further reported that application of proline to plants under high temperature stress (45/40 °C) reduced injury to membranes and had improved chlorophyll and water content due to enhanced levels of antioxidants. Cai et al. (2014) observed that indole acetic acid, gibberellic acid, and abscisic acid significantly improved the grain yield in wheat under high temperature stress.

7.7.2.2 Phytohormones

Salicylic acid improved the efficiency of photosynthesis in maize thereby, improving the plant growth and yield (Khan et al. 2003). Salicylic acid increases the protein levels in plants (Apostolova et al. 2008), whereas application of 1 mm SA reduces transpiration (Azizi 2010). The salicylic acid acts as an antioxidant, neutralizes free radical damage due to oxidation and degradation of protein structure, and thus increases protein content (Keshavarz 2010). Iqbal et al. (2013) reported that application of 0.5 mm SA reduced the loss of chlorophyll, rubisco activity and showed maximum protection from heat stress by lowering ethylene formation through the decrease in ACS (1-aminocyclopropane carboxylic acid synthase) activity. Dat et al. (1998) found that foliar application of salicylic acid in lower concentration to mustard increased the H_2O_2 level and reduced the catalase which amplifies the potential of plants to withstand the heat stress.

Farooq et al. (2008) reported application of α-tocopherol and SA decreased consumption of photosynthates and increased membrane stability which aided in transport of photosynthates, thereby increased yield. Rao et al. (1997) concluded that SA acts as a prooxidant and phytotoxin if applied at concentration more than 1 mmol/L. Abscisic acid (ABA) as a plant growth hormone regulates stomatal opening and root hydraulic conductivity (Hartung et al. 1998; Hose et al. 2000, 2001) and also induces tolerance to abiotic stresses such as temperature, drought, and salinity (Giraudat et al. 1994).

7.7.2.3 Signaling Molecules

Nitric oxide (NO) acts as a signaling molecule for many physiological processes and plays an important role in plant's tolerance to high temperature (Hasanuzzaman et al. 2012; Waraich et al. 2012). Hossain et al. (2010) reported that excessive NO production under high temperature resulted in the thermoinhibition of seed germination in *Arabidopsis thaliana*. The exogenous application of NO-protected seedlings of wheat from high temperature induced oxidative stress by upregulating antioxidant defense and glyoxalase system (Waraich et al. 2012; Hasanuzzaman et al. 2012).

7.7.2.4 Trace Elements

Selenium serves as a stress protectant to various environmental stresses including high temperature. Djanaguiraman et al. (2010) reported that the foliar application of selenium (at 75 mg L^{-1}) decreased membrane damage by enhancing antioxidant defense resulting in higher grain yield. Selenium application significantly increased stomatal conductance, photosynthetic and transpiration rate by 12, 13, and 8%, respectively, compared with the unsprayed control. Waraich et al. (2012) reviewed various approaches of micronutrient application in plants and concluded that low concentration application of plant nutrients provides tolerance against high temperature stress.

7.7.2.5 Nutrients

Application of essential nutrients like nitrogen, phosphorus, and potassium improves plant vigor under moderate heat stress (Dupont et al. 2006). Nitrogen in the form of nitric oxide (NO) protects the plant from high temperature stress by directly acting as an antioxidant and as scavenger of reactive oxygen species formed due to high temperature (Wendehenne et al. 2001). Song et al. (2006) revealed that NO acts as a signal molecule to activate active oxygen-scavenging enzymes which induce thermotolerance in plant. Under high temperature stress, foliar application of thiourea promotes root growth by enhancing assimilate partitioning to root at seedling and pre-anthesis growth stages resulting in increase in number of grains per spike, 100 grain weight, and crop yield (Anjum et al. 2011).

Under stress conditions potassium is involved in several physiological processes, like photosynthesis, translocation of photosynthates, turgidity maintenance, and enzyme activation (Marschner 1995; Mengel and Kirkby 2001), and the deficiency of potassium resulted in decrease in photosynthetic rate, improper partitioning, and utilization of photosynthates. Potassium nitrate has been extensively used to mitigate the effect of heat stress in wheat. Application of zinc can also help to improve heat tolerance in wheat (Graham and McDonald 2001).

Calcium (Ca) as secondary nutrient plays a vital role in preserving the structural and functional integrity (Coria et al. 1998) and stability of cell membranes and regulates ion transport as well as enzyme activities (Marschner 1995; Rengel 1992; Yang and Poovaiah 2002). Ca^{2+} directly activates some antioxidant enzymes (Brookes et al. 2004 and Farooq et al. 2008). Several studies (Knight and Knight 1992; Nayyar 2003; Bhattacharjee 2008) proved involvement of calcium in enhancing the plants ability to withstand various stresses including heat. Increased cytosolic calcium content under heat stress helps plant cells to survive (Wang and Li 1999). Calcium is involved in signal transduction involving new gene expression under oxidative and temperature stress (Trofimova et al. 1999). Calcium was also found to control guard cell turgor and hence stomatal aperture (Mansfield et al. 1990; Webb et al. 1996). The foliar application of potassic fertilizer, urea, and zinc may help in improving crop yield by alleviating the ill effects of high temperature.

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Identifying Suitable Soil Health Indicators Under Variable Climate Scenarios: A Ready Reckoner for Soil Management

8

Joydeep Mukherjee, Nilimesh Mridha, Surajit Mondal,
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Abstract

The increase of greenhouse gas emissions due to anthropogenic activities is continuously changing the climate. The soil is the important factor for the global food production and also responsible for three important greenhouse gases, viz. carbon dioxide, methane and nitrous oxide. These gases are highly contributing in the global warming, which directly affects the soil health. The change in physical, chemical and biological properties of soil system changes the organic carbon content, nitrogen mineralization, availability of essential nutrients and soil hydrological properties, along with the soil aggregate changes. Increased soil temperature is also enhancing the microbial activities in the soil and ultimately causes the decrease in the soil organic carbon and increase the gaseous carbon emission. In the present chapter, the maintenance of the soil health and soil quality in the variable climate are discussed, and the agricultural practices such as maintaining permanent vegetative cover on the soil surface, crop residue incorporation and lowest disturbed soil are recommended to protect the soil surface. These methods also support to mitigate the greenhouse gas emission from the agriculture soil.

Keywords

Soil health · Climate change · Greenhouse gas · Global Warming and CO_2

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8.1 Introduction

Climate change is the apparent and long-term shift in the weather conditions at a place over a time segment that ranges from decade to thousands of years. The continuous and rigorous efforts by the scientists from various streams and the studies carried out by them throughout the world have resulted in the identification of multitude of factors that possess ability to influence the climate in one way or another. In fact historical studies have revealed that climate change has been found to be related to, if not the cause behind ancient civilization collapse, human migration and ever-changing faces of agriculture. The World Meteorological Organization and the UN Environment Programme in 1988 urged to set up international scientific body to provide an objective and unbiased source of information on climate change. The Intergovernmental Panel on Climate Change (IPCC), which encompasses more than 1300 scientists from different countries, releases periodic assessment reports that are critically assessed and approved by experts and governments. IPCC's Assessment Report (IPCC 2007) showed that the developing countries will be the worst sufferers due to impacts of climate change which will threaten the achievement of the Millennium Development Goals, poverty reduction and food security. IPCC forecasts about 2.5–10 °F rise in temperature over the next century.

A big challenge to the agricultural production is to meet the burden of growing global population, and a big share of development aid goes to the agricultural sector which contributes largely to greenhouse gas emission and climate change. Advancement of remote sensing techniques is now capable to foresee the climatic situations in the future using satellite data and by assimilating various types of information about our planet and its climate on a global scale over the periods. The results of climate data analysis over many years show the indications of a changing climate.

Different factors such as variations in solar radiation, deviations in the Earth's orbit, mountain-building and continental drift and changes in greenhouse gas concentrations which affect climate significantly are often called climate forcing. The anthropological factors are the influence of human activity to environmental and climatic changes. It has been agreed by scientific community that human activity is causing the Earth to get hotter rapidly over the past several decades. Anthropogenic factors like fossil fuel burning followed by aerosols (of which particulate matter is the biggest threat) and cement production contribute significantly in rising CO_2 levels. Besides, ozone depletion, land use, deforestation and animal agriculture are also affecting climate individually or concurrently.

8.2 The Future Consequences of Global Climatic Change

The adverse consequences of climate change are projected to happen globally in the future in the form of lengthier drought periods; an increase in the number, duration and intensity of tropical storms; and frequent wildfires and various other forms that have already started with discernible effects on the environment. Some of these greatest threats that we are experiencing include sea level rise; loss of sea ice;

shrunken glaciers; longer, more intense heat waves; shifting of plant and animal species; and early flowering.

A strong and compelling forecast made by scientists with high confidence is that global temperatures will continue to increase for the coming decades, basically due to greenhouse gases produced by anthropogenic activities. The Intergovernmental Panel on Climate Change (IPCC), which includes more than 1300 scientists all over the world, makes prediction of temperature rise by 2.5–10 °F over the next century. According to the IPCC, the regional impact due to climate change will vary depending on the capability of social and environmental conditions to adapt the extent of climate change effects and mitigation measures adopted. Forecast given by IPCC also indicates that the beneficial effects will be observed in some regions and damaging ones in other regions if the rise in global mean temperature remains less than 1.8–5.4 °F above 1990 levels. Over the periods, the rise in global temperatures will increase net annual costs.

The regional effects of global climate change forecast by the IPCC are:

- By 2050, it is projected that the freshwater availability will decline mostly in southern, central and south-eastern part of Asia.
- Increased death rate from diseases linked to flood and drought in some regions.
- Studies of 69 model-based outputs exhibit some trends in cereal yield variation in spite of having wide range of variability of yield due to changes in temperature and CO_2 fertilization. Temperature rise up to three degrees results in increased yields in mid- to high latitudes but shows diminishing impact when temperature changes are greater than 3 degrees (Easterling et al. 2007).
- Stronger yield-diminishing impacts are found in tropical and subtropical regions for all crops, which reflect a lower growing temperature threshold capacity in these areas. Also, it has been found that global agricultural production capacity is anticipated to decline by 16% without CO_2 fertilization and by 3% if it is considered with overall reduction by 9–21% in developing countries due to global warming (Cline 2007). But the industrialized countries will gain 8% increase or will lose by up to 6%, depending on carbon fertilization and without considering the effects of increased losses due to more frequent extreme weather events (droughts or floods), increased problem of water shortage and insect pests.
- Increased risk in coastal areas due to frequent flooding.

8.3 Global Climate Change and Agriculture Sector

Developing countries will be affected much more economically due to climate change as economic development of these countries predominantly depends on agriculture which shares a large part of gross domestic production and employment. The agriculture sector which involves indiscriminate fertilizer use (Fagodiya et al. 2017a; Pathak et al. 2016), paddy cultivation (Malyan et al. 2016a, b; Gupta et al. 2016a, b), livestock rearing and related land clearing along with land-use change acts as a prominent source of global greenhouse gas emissions in the atmosphere and influences carbon sequestration and storage (Bhatia et al. 2013a). So, the fearing threat of enduring climatic change to the agricultural production itself serves as opportunities for reductions in greenhouse gas emissions. The constant accumulation of greenhouse gases in the atmosphere is warning shifts in climate throughout the globe that will disturb growing conditions and agroecological environment.

A study conducted by Kumar et al. (2001a, b) revealed the effect of climate change on crop yields, welfare and GDP of India. They estimated that yield losses for rice and wheat would vary between 32% and 40% and 41% and 52%, respectively, without CO_2 fertilization based on the projected range of temperature rise of 2.5–4.9 °C for India, and GDP would fall between 1.8% and 3.4%. However losses would be slightly smaller without CO_2 fertilization. Their study also revealed that even with farm-level adaptations, climate change would significantly affect the Indian agriculture. As per the estimation, a fall of 9% in farm-level total net revenue with a concurrent change of temperature by +2 °C and precipitation by +7% would occur, whereas the fall in farm-level total net revenue would be nearly 25% with a concurrent change of temperature by +3.5 °C and precipitation by +15%.

8.3.1 Climate Change Forecast for the Indian Subcontinent

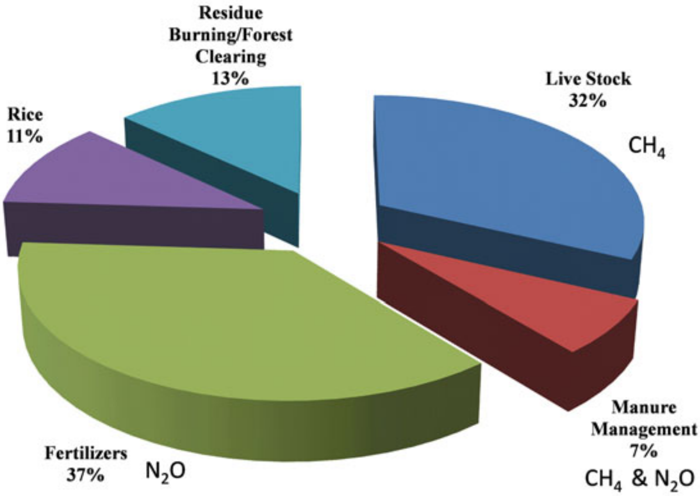
Studies on climate change forecast showed that semiarid regions of western India may receive a higher amount of rainfall over normal due to temperature rise, while a decline of 10–20% in winter rainfall is expected over central India by the 2050s (Aggarwal et al. 2005).

The following are the forecasts of Indian agriculture as affected by the changing global climate:

- The impact of increase or decrease of rainfall as well as shifts in the rainfall timing will affect the agricultural sector adversely.
- The coastal areas of Gujarat and Maharashtra will be worst affected as fertile and cultivated soils are very much prone to salinization as well as waterlogging due to cyclonic activity.
- A high chance of reduction in pearl millet production by 10–15% with an increase of 2 °C in temperature over Rajasthan.
- Climate change will also affect the Indian agriculture by altering the population of pests or weeds and soil properties like soil moisture which is controlled by rainfall, evaporation and runoff.

8.4 Studying the Interrelation of Global Climate Change and Agriculture

Climate change is the consequence of a rise in the greenhouse gas (GHG) concentration like carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). About 11% of total greenhouse gases are emitted by the agriculture sector. In the coming



Source: Drawn from data represented in USEPA (2006)

Fig. 8.1 Emission of GHG from the agriculture sector as source of global climate change

decades, these emissions in developing countries are expected to rise due to population and income growth, among other factors. Within the agricultural sector, manure and livestock management, fertilizer application, rice cultivation and residue burning are the major sources of emissions (Gupta et al. 2015). Agriculture can play a decisive role in the mitigation of greenhouse gases in developing countries, but the economic potential for mitigation is inhibited by poor incentives to invest in this area. Developing countries are accounted for three fourths of global technical potential, with Asia accounting 40%, Africa 18% and Latin America and the Caribbean 15% (Smith et al. 2007).

Four principle subsectors contribute maximum share of emissions in agriculture. These are wetland rice cultivation, agricultural soils, manure and livestock management and burning of crop residues and deforestation (Fig. 8.1).

Nitrous oxide (N_2O) is considered as a major source of GHG emissions in agriculture, accounting for about 38% of the global total. N_2O gets produced naturally in soils through nitrification and denitrification processes (Kumar et al. 2016). Agricultural activity involves addition of nitrogen to soils either directly or indirectly. Direct additions occur through application of nitrogen fertilizer, addition of livestock manure and sewage sludge, growing of N-fixing crops and forages, crop residue retention and cultivation of soils (Bhatia et al. 2013b) that have higher organic matter content (Fagodiya et al. 2017a). Volatilization and subsequent atmospheric deposition of applied nitrogen, surface runoff and leaching of nitrogen into groundwater and surface water are considered as indirect additions (Pathak et al. 2016). Rise in use of N-containing fertilizer, both synthetic and organic, for higher crop yield will likely to play a key role in growth of N_2O emissions (Fagodiya et al. 2017b; Kumar et al. 2016). It is predicted that the sharpest increase in fertilizer application will occur in developing countries and they are likely to use 36 million tons more fertilizer than developed countries by 2020 (Bumb and Baanante 1996).

8.5 Indicator of Global Climate Change

Natural ecosystems believed to be more vulnerable to changing climate than managed ones. Additionally, natural ecosystems may not only be affected by climate change but by subsequent stresses resulting from human responses to those changes, like increased irrigation, expanded tillage or grazing and diversion of water from streams. Besides, improper management in forestry and agriculture could make even some managed ecosystem vulnerable to climate change. There are wide variations in climate change vulnerability, and how a system will respond to changing climate is difficult to predict. For detecting stress in a natural resource system, soil moisture monitoring may be a best indicator.

Soil moisture is generally more important for vegetation than total precipitation (Pathak et al. 2014), and it may decrease for two reasons. Firstly, with increase in temperature, the rate of evapotranspiration increases. This increased evaporation rates may deplete the soil moisture at a faster rate than is supplied by the higher precipitation during summer months. Secondly, the changing runoff patterns due to increased precipitation can also affect the soil moisture storage. Every soil has limits to absorb moisture and is called water holding capacity. For example, sandy soils due to their porous nature transmit water relatively quickly through soil column to surface or groundwater system. However, clay soils have very low percolation rates. If increased precipitation is not evenly well distributed over the year and comes in a few large storms, then more of it may be lost as runoff rather than remaining in the soil. Therefore, increases in annual precipitation may not result in higher soil moisture but rather could be accompanied by drier conditions.

Simulation studies conducted in the United States (Halpin 1993) projected soil moisture based on the climate changes by two general circular models (GCM): (i) the Goddard Institute of Space Studies (GISS) scenario and (ii) Geophysical Fluid Dynamics Laboratory (GFDL) scenario. A soil moisture index was calculated as the ratio of moisture available to potential moisture demand (calculated as the ratio of actual to potential evapotranspiration). White areas in the maps show regions of non-significant change in the moisture index, while dark shading indicates areas of drying, and lighter shading depicts relatively wetter areas. The Goddard Institute of Space Studies (GISS) scenario gives a mixed result, with considerable areas of moderate drying with patches of wetting particularly in the Southeast and Northern Rocky Mountain States. The Geophysical Fluid Dynamics Laboratory (GFDL) scenario produces the most extreme result for North America, with significant drying in the eastern and central United States and along the Pacific Coast.

According to GFDL (Geophysical Fluid Dynamics Laboratory) scenario, except tundra and deserts, all other existing ecosystems are shifting towards drier regimes of climate. Under this scenario, major portion of agricultural lands (about 80%) in the United States are facing drying. However, the GISS scenario produces a natural cover with a mix of wet and dry areas and also produces some noticeable drying in the wetlands.

8.6 Global Climate Change and Soils

According to a report by the European Commission in April 2010, poor soil management could aggravate the effect of climate change. Soil is considered both as a sink and source of greenhouse gases, and it contains twice the amount of carbon in the atmosphere and thrice the amount in vegetation, globally. If stored carbon is released from the soil to the atmosphere, and if nitrous oxide and methane emission increases, then climate change will be aggravated. Contrary to the above, if more carbon is sequestered in soil and the emission of greenhouse gases decreases, climate change will be delayed.

World's soils, containing about 73–79 billion tonnes of carbon, acts as a major carbon reservoir. A 0.1% loss of soil carbon in Europe can create havoc to atmosphere and equals to the emission from 100 million extra cars. Current soil degradation rate needs to be contained or reversed with sustainable management practices to boost carbon sequestration as a means of slowing climate change. An enormous quantity of carbon from the atmosphere can be absorbed to the soil through proper management and gives us valuable time to reduce greenhouse gas emission and move towards sustainability. Conversion of grassland, forest or native vegetation to cropland results into emission of stored carbon as carbon dioxide to the atmosphere. Due to world population growth more areas are being converted to cropland and if continues then in one soil will be source rather than sink. Agricultural practices like maintaining permanent vegetative cover on the soil surface, application of crop residues and minimum disturbance of soil can effectively protect the soil surface from water and rain and facilitate carbon retention by soil.

There is lack of documented evidence regarding the positive or negative impacts of climate change on terrestrial carbon stock. There is no strong and clear evidence for either an overall or combined positive or negative impact of climate change (raised atmospheric CO_2 concentration, temperature, precipitation) on terrestrial carbon stocks. Soil C is affected by almost all the factors of climate change either directly or indirectly. Increased CO_2 concentration in the atmosphere can enhance soil C stocks through higher photosynthesis rate (Jastrow et al. 2005) and can lower down the C content by increased temperature (Rustad et al. 2001).

8.7 Soil System and Factors Affecting Climate Change

8.7.1 Human-Induced Climatic Change

Human activities are adverse affecting climate change and also accelerating the pace of the global warming. These factors are known as anthropogenic factors of climate change. Sometimes, these factors are direct and cannot be avoided (like the effects of irrigation on humidity), while some other factors have complex relation with climate change. Different theories have been hypothesized and debated by many researchers over the years. It is now believed that human activities are the likely cause of increased global average temperature over the last decades. Now the main concern is how the human impact can be reduced and to find ways to adopt in the changing environment. CO_2 released from soil system due to clearing of forest land and improper use of land needs to be contained to check the rate of climate change. Improper agricultural practices include overuse of chemical fertilizers and pesticides and increase cultivation of grain crops which are great miner of soil nutrients. Deforestation, draining of wetlands and cultivation of prairie and forest lands are causing oxidation of trapped organic matter and releasing a significant amount of CO_2 into the atmosphere Therefore global average temperature is likely to increase for the next several decades, and significant human intervention is needed to reduce the rate of increase (IPCC 2014; Mina et al. 2017).

8.7.2 Soil System and Soil Properties Critical to Climate Change

Soil system which plays a major role in balancing all the three major greenhouse gases is facing unique challenges due to climate change. Soil stores more carbon than the combined pool of atmospheric carbon dioxide and animals and plants. Soil is the largest source of nitrous oxide and also an important source of methane. Emissions of these gases are largely controlled by the complex interaction of water regime of land and soil biota. Therefore, these biotic processes need to be understood before applying any effective control measures.

Key conditions of soil are getting affected by global climate change resulting in profound land-use changes which in turn lead to degradation of soil resources due to decline in biotic and abiotic parameters. Therefore it is necessary to secure or maintain soil quality under global climate change scenario. Among the soil quality indicators, soil organic carbon is the most important parameter, and it plays a vital role in soil fertility and protects soil from physical degradation (Fig. 8.2) across various ecosystems (Burke et al. 1989; Dalal and Chan 2001). Organic matter in soil acts as a food for soil microbes, acts as cementing agents and plays a major role in aggregate formation and also supplies essential plant nutrients like nitrogen, phosphorus and potassium. Cation/anion exchange capacity, i.e. ability of a soil to retain ions and nutrients, is also enhanced due to presence of organic matter (Muckel and Mausbach 1996). Thus climate change may shift the equilibrium of many soil processes either directly or indirectly. These processes include oxidation of soil

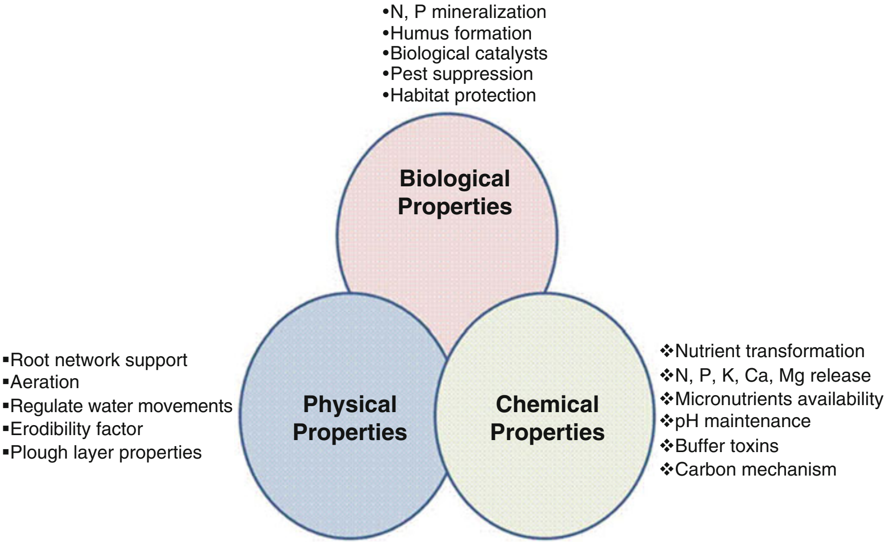


Fig. 8.2 Vital components and processes in soil system

organic matter, nitrogen and carbon cycling, erosion, acidification, salinization and all those processes which ultimately affect the soil health. A few important key factors that have great potential to get affected by global climate change are presented below:

8.7.3 Soil Organic Carbon

Soil organic matter is defined by Brady and Weil (2004) as the organic fraction of the soil that includes plant and animal residues at various stages of decomposition, cells and tissues of soil organisms and substances synthesized by the soil population. The organic fraction due to its colloidal nature has significant impact on the chemical and physical properties of soil. About one third of the cation exchange capacity of surface soils is contributed by organic fraction of soil, and it is the most important factor for aggregate stability.

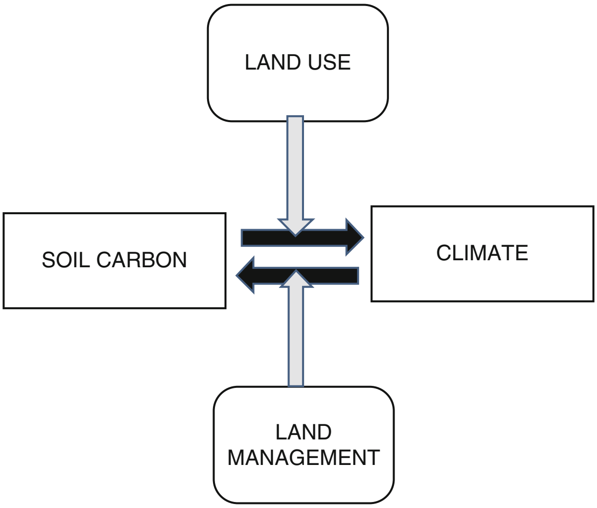
The soil carbon pools are fairly well buffered due to their larger size and slow turnover rate, and therefore short-term effects that do not involve removal of carbon from landscape have no immediate effects on soil carbon pools. Any management practices usually take 5–10 years to produce any measurable increase in soil carbon, fertility and tilth. However, losses can be at a faster rate due to improper management. It is very difficult to accurately measure changes in soil carbon over a few years due to its highly variable spatial distribution and larger size of pools. The increased concentration of greenhouse gases and its subsequent effects on global warming are the most debated issues. Kyoto Protocol suggested two ways for reducing carbon dioxide from the atmosphere: one way by removing atmospheric CO_2 through fixation and another way by decreasing the emissions. Therefore, the probability of using terrestrial vegetation or ecosystem as carbon sinks has been established as one of the most important strategies to reduce the CO_2 concentration from the atmosphere. Considering the size of the pools, it is highly relevant for reducing the pace of climate change and soil physical degradation. A small change in such large pool can have dramatic impacts on atmospheric CO_2.

The processes of storage and loss of soil carbon are dependent on climate. Therefore, soil might have important feedback to the changing climate. If the entrapped carbon is released from soil as CO_2 or there is increased emission of CH_4 or nitrous oxide, then climate change will be accelerated. On the other hand, if more carbon is accumulated in soil through various processes, then climate change will be retarded.

Agricultural land and forest can be taken as potential carbon sink as mentioned in Kyoto Protocol. However, carbon sequestration is a highly debatable issue due to the size of the sink, sustainability of the stored carbon and overall its accounting. It is highly relevant across Europe due to the susceptibility of soil to desertification (like Spain, Italy) and peat and muck soils with large amount of organic matter in the north (like Finland, Scotland) or the major agricultural areas that are managed intensively (France, Germany, the Netherlands, the United Kingdom). The organic matter status of those areas is expected and anticipated to further decrease.

Land use affects the balances of carbon between soil and atmosphere (Fig. 8.3). A land-use change induces change in the balances. For example, afforestation of a degraded land could result in sequestration of atmospheric carbon, and similarly,

Fig. 8.3 Interrelationship of soil carbon and climate change as affected by change in land use and management



ill-managed agricultural soil may release either sequestered soil carbon to the atmosphere. Therefore, land use can play a decisive role in carbon cycle and can be used as a successful strategy to counteract the bad effects of climate change. It can mitigate the climate change if more carbon is accumulated or emission is reduced.

8.7.4 The Properties of Clay Surfaces and Structural Stability of Soils

The clay content and structural stability of a soil have profound impact in its buffering capacity, i.e. ability to resist against the adversities of climate change. There are three broad categories of soil based on clay content and structural properties.

A. Ferralsols and Nitisols: These types of soil occupy large areas of tropics and naturally have high structural stability. The former soils are predominantly found in the northern side of South America, while the latter are mostly abundant in East Africa. The clay particles are generally covered by iron and aluminium oxides or hydroxides, but the composition of clay portion may be different. The oxides or hydroxide surfaces could be from high iron and aluminium-containing parent material under prolonged hydrolysis by water (containing CO_2).
B. Contrary to the above, at the other extreme, there are soils of very low structural stability and are prone to failure under load or stress (like quick clays). The clay minerals are usually covered by a gel-like amorphous material with high amount of silica (McKyes et al. 1974). These types of soils are presumed to be developed in earlier periods through the process of reverse weathering from strongly saline parent materials. Quick clays of the Champlain Sea sediments in Ontario and Quebec are examples of such soils. Lands that have high proportion of these types of soil are likely to produce higher runoff and suspended sediments and also liable to mudflows in sloppy topography. Andosols, derived from volcanic parent materials, have low stability and are prone to thixotropy.
C. The above two extreme types encompass most of the soils, while vertisols have medium to low structural stability and have small amorphous coating on the clay surfaces. When Planosols originated through the process of ferrolysis have low cation exchange capacity and swell shrink potential due to presence of smectite and illite interlayered with aluminium hydroxides polymers. Some amount of iron oxides also leached out during the ferrolysis process, reducing its structural stability. Global climate change may have more impact in regions that have these kinds of soils (like central parts of India, the black cotton soils).

8.7.5 Soil and Atmospheric Gas Flux Equilibrium

Depending on the management and local conditions, a soil may act as a sink or a source of greenhouse gases. The balance between this two is very delicate. Soils globally not only contain twice the amount of atmospheric carbon, but also the flux between soil and atmosphere is considerably large and about ten times the flux of CO_2 from fossil fuels. Permafrost and water-logged soils hold a major portion of carbon stocks, but these types of soils are also important emitters of CH_4 and N_2O.

About 25% of the global greenhouse gas is contributed by farming activities and agriculture. Currently agriculture practices adversely affecting soil/air/water ecosystem (Batjes 1996; Janzen 2004) lead to imbalance. Soil organic C content is reducing day by day, while increase in CO_2 concentration has been detected in agriculture. Carbon content of soil can be maintained or increased, and non-CO_2 greenhouses gas emission can be reduced by appropriate soil management practices and by using decomposed organic matter like manure, vermicompost, etc. These practices influence C and N cycles, nutrient content and population of microbes in soil, which play crucial role in the emission of CO_2, CH_4 and N_2O (Huang et al. 2004; Paillat et al. 2005). Therefore, it is crucial to assess such activities as to its effectiveness and adverse or harmful environmental effects.

8.8 Global Climate Change and Anticipated Change in Soil System

The interaction of various factors of climate change with the crucial soil dynamics and processes has potential to change many of its properties in a number of ways. The changes in soil microbiological, chemical and physical properties are mostly influenced by the perturbation in the air temperature, rainfall and CO_2 concentration. It is a well-known fact that soils are formed due to the interaction of five main factors, namely, parent material, topography and relief, organisms, climate and time. Due to the change in climate, the main soil-forming factor, the process of soil formation has been influenced a lot. Changes in climatic variables such as temperature and rainfall have influenced the soil temperature and moisture regime directly, which in turn have influenced the habitat of soil organisms. The modification of the distribution of soil microorganism would influence the soil organic matter decomposition. Increased temperature would speed up the activities of the soil microorganism which may benefit the soils of humid and subhumid regions by the gradual improvements in its fertility. Poleward retreat of the permafrost boundary would be one of the major changes in the future (Goryachkin and Targulian 1990). The other radical changes in soil would be related to the rate unlike the type mentioned above. As a result of the changes, certain soils may face widespread changes from one major soil-forming process to another, such as tropical soils in the Amazon region which are having low physical-chemical activity (Sombroek 1990).

Before studying the detailed effects of the changing climate on soil health, let us observe the key processes in soil systems which are sensitive to altering climatic conditions. The study of climate-sensitive soil processes is very important at this stage. Effect of climate change on vital pedogenic processes is presented in the following section.

8.8.1 Soil-Forming Processes

It is generally found that the normal processes of soil formation are maintained. But under some specific condition, with mostly fragile soils, even a little change in external conditions may invite a major change in the dominant soil-forming process. Sombroek (1990) illustrated these changes with the four examples such as a change from hydrolysis to cheluviation (ferralsols to podzols); irreversible hardening of the subsoil; clay illuviation forming dense subsoil in originally homogeneous, porous ferralsols; and salinization. The soils with significant amount of weatherable minerals may benefit from the positive effects of increased rate of weathering.

8.8.2 Soil Organic Carbon

Soil carbon pools are greatly influenced by climate change as it affects almost all the processes of C cycle, namely, assimilation of C through photosynthesis, respiration, falling of litter and its decomposition and erosion from surface along with the hydrological transport. Soil and atmosphere always share a large gross exchange of CO_2. As soil has a large stock of carbon and due to the extent of the exchange, a relatively little change in the exchange fluxes of CO_2 may affect both the atmosphere and soil in a great way. Hence proper management of these fluxes can considerably add to the climate change mitigation potential. The activities that add more carbon to the soil and trap them are called carbon sequestration mechanisms. These include conservation agriculture practices or activities which slow the rate of release of trapped carbon into the atmosphere through burning, tillage and soil erosion. In this way the trapped or sequestered carbon resides in the soil as soil organic carbon (SOC). It is estimated that soil carbon sequestration accounts for about 89% of the technical mitigation potential in agriculture, compared to 11% for emissions abatement (Smith et al. 2007). Several agricultural practices are reported to increase the SOC content in the soil, to name a few like zero/minimum/no tillage practices, crop rotation and diversification, restoration of degraded soil, improved management of pasture and grazing land, proper irrigation and nutrient management, etc. SOC present in the terrestrial biosphere can act in both directions, i.e. sometimes as source and sometimes as sink of atmospheric CO_2 based on land management, thus contributing towards acceleration or mitigation of greenhouse effect (Lal et al. 2004).

Elevated CO_2 experiments, both in chamber-type or free-air enrichment, have reported rapid enhancement in SOM dynamics along with increased soil microorganism activity which may cause temporary competition for plant nutrients. Occasionally, these are reported as negative effects of elevated CO_2 on plant response. However, enhancement in soil organic matter content and its dynamics along with the microbial activity are going to help plants by increasing the amount of available nutrients in the soil in the long run.

8.8.3 Influence on the Soil Chemical Properties and Nutrient Supplying Capacity of the Soil

Climate change will increase the rate of reaction in the soil. There will be increase in the rate of mineralization. Hence lots of salts and cations will be available in the soil solution. These could be either taken up by the plant or leached out of the root zone due to heavy rainfall or move upward and cause salinization if rainfall is less or evapotranspiration is high. The following are some possible effects of climate change on the soil chemical properties:

1. High-intensity rainfall events in places having low vegetation cover can leach out the salts created in the soil in some well-drained sites, result into heavy runoff under poor drainage and ultimately deposit all these salts in the area where depression is present, causing salinization.
2. Soils having adequate cation exchange capacity and anion sorption to minimize the loss of nutrients during leaching and highly stable and strong heterogeneous network of interconnected macropores to maximize the bypass flow may be resilient under climate change condition.
3. Increased temperatures, mainly in arid climate, cause a higher evaporative demand. In case of ample abundance of soil moisture, e.g. irrigated areas, enhanced evaporative demand could lead to soil salinization if proper water management or irrigation scheduling or drainage is not followed. Some recent experiments by the Salinity Laboratory, Riverside, California, reported the increased salt tolerance of crops under high atmospheric CO_2 conditions (Maas 1986; Bowman and Strain 1987).
4. Transient salinity may increase in sodic soils as capillary rise plays the predominant role bringing salts to the root zone. As in these soils, the surface crust or sealing is found; hence the possibility of desalinization by periodic rainfall is also very low. Moreover, enhanced drying of subsoil builds the salt concentration in the soil solution.

8.8.4 Physical Properties and Structural Stability of the Soil

Generally little change is seen in the mineral composition of clay and coarser fractions over the centuries. Though few exceptions such as perennially moist volcanic soils subject to drying would contain transformed halloysite mineral developed from X-ray amorphous material. Sometimes soils which are exposed to higher temperature or severe drying might have haematite developed from gradual dehydration of goethite. Surface properties of the clay might change at much faster rate than general change in crystal structure or bulk composition. These changes may have pivotal effect on chemical and physical properties of soils (Brinkman 1985, 1990).

The following points are about those transformation processes which are responsible for bringing the changes in the surface of clay minerals or composition of it (Brinkman 1982). The climate change can accelerate or inhibit each of them.

1. Water dissolved with carbon dioxide may hydrolyse the soil, removing its basic cations and silica.
2. Cheluviation, in which aluminium and iron may get dissolved and removed by chelating with organic acids.
3. Ferrolysis, a cyclic process of clay transformation and dissolution mediated by alternating iron reduction and oxidation, which decreases the cation exchange capacity by aluminium interlayering in swelling clay minerals.
4. Strong mineral acids may dissolute clay minerals, generating acidic salts of aluminium and amorphous silica.
5. Reverse weathering may end up producing minerals such as, e.g. montmorillonite, palygorskite or analcime, under neutral to strongly alkaline conditions due to clay formation and transformation.

Among these processes, hydrolysis and cheluviation may get accelerated by increased leaching rates. In a warmer condition in the future, soils subjected to reduction and leaching along with oxidation may evidence ferrolysis, which may extend to a larger region in high latitudes and monsoon-dominated climate. Dissolution is possible to occur in the coastal plain with good drainage as strong acids may form in these areas provided sulphidic materials are present in ample quantity, though this may not be possible due to the rise in sea level. The arid region or region which may become dry due to climate change may face reverse weathering. The envisaged changes as consequence of climate change would take centuries time to take place which may influence the surface properties of clay fraction. On the contrary, direct human intervention may lead to much acceleration of these processes, for example, acid rain severely affected the sandy soils of some parts of Europe (Van Breemen 1990), or those soils which remain seasonally inundated by water evidence extreme rapid ferrolysis such as the Volta Lake in Ghana (Amatekpor 1989).

Comparatively weak aggregates which are unable to withstand influence of the rapid water uptake show the signs of slaking. The process can be resulted from processes such as disparity in the swelling of clay, trapped and escaping air in the pores of soil, heat release occurring rapidly while wetting process and most importantly the mechanical effects of the flowing water. Slaking gets affected by factors like the rate of wetting, water content of soil, soil texture, clay type and organic matter. It gets enhanced due to fast wetting rates, especially in case of initially dry soils. Continuous and repetitive tillage activities cause loss of organic matter in the soil and breakdown of the aggregates. The loss of organic matter indirectly leads to the increased slaking by reducing the stability of soil aggregates.

An important but a bit slower process is the reddening of brown soils, which experience increased duration of high temperature during summer along with dryness. Here, the haematite would become more stable over the goethite, the presently dominant one. This mineralogical change might be able to decrease the phosphate fixation intensity and amount. Buol et al. (1990) have given an overview of such changes, with emphasis on temperate climate zones.

8.8.5 Soil Biological Properties

Soil biological properties will be influenced a lot by the climate change. The increase in duration of above optimum soil temperature will increase microbial activity and hence lower the organic matter content which may not be compensated by the possible increase in net primary productivity. The increase in heavy rainfall events may lead to water-saturated soil condition which will subject the soils to reduced condition.

1. Soil biological properties in general and microbial populations in particular might undergo a massive change with elevated CO_2 coupled with changed moisture and thermal temperature regimes. Dynamics of nutrient and many soil-borne diseases will change due to the change in its drivers.
2. Microbial activity enhancement owing to the availability of higher CO_2 and temperature produces polysaccharides and other soil stabilizers in greater amounts. Higher vegetative growth of crops will increase the litter or crop residues, root, etc., increasing the amount of organic matter content which will again stimulate the activity of soil macrofauna, including earthworms. It will create stable bio-pores, improving the infiltration rate and bypass flow. Enhanced soil stability and better infiltration make the soil resilient from water erosion. Greater proportion of bypass flow also decreases the leaching loss of nutrients due to heavy rainfall.
3. As the microbial activity tends to increase, it will lead to faster recycling of plant nutrients through soil organisms. Higher CO_2 concentration leads to increased production of root material (without the temperature increase), increasing the soil organic matter content, which also undergoes a temporary immobilization followed by cycling of larger amount of plant nutrients. But some researchers have reported higher C/N ratios in litter under high CO_2 conditions, which would cause lower rate of decomposition and mineralization of the plant nutrients from the litter. The increase in "stable" portion of soil organic matter content might be counteracted by higher soil temperatures, but it will surely boost the microbial activity.

8.8.6 Soil Hydrological Properties

Soils are most resilient against the effects of such increasing aridity, and rainfall variability would have a high structural stability and a strongly heterogeneous system of continuous macropores (the same as in the tropics), hence a rapid infiltration rate, as well as a large available water capacity and a deep groundwater table. In boreal climates, the gradual disappearance of large extents of permafrost and the reduction of frost periods in extensive belts adjoining former permafrost are expected to improve the internal drainage of soils in vast areas, with probable increases in leaching rates.

The change in temperature and rainfall factors has direct effects on the soil water dynamics. In the humid tropics and monsoon climates, increased intensities of rainfall events and increased rainfall totals would increase leaching rates in well-drained soils with high infiltration rates and would cause temporary flooding or water saturation and hence reduced organic matter decomposition, in many soils in level or depressional sites. They would also give rise to greater amounts and frequency of runoff on soils in sloping terrain, with sedimentation downslope and, worse, downstream. Locally, there would be increased chances of mass movement in the form of landslides or mudflows in certain soft sedimentary materials. Soils most resilient against such changes would have adequate cation exchange capacity and anion sorption to minimize nutrient loss during leaching flows and have a high structural stability and a strongly heterogeneous system of continuous macropores to maximize infiltration and rapid bypass flow through the soil during high-intensity rainfall. In temperate climates, minor increases in rainfall totals would be expected to be largely taken up by increased evapotranspiration of vegetation or crops at the expected higher temperatures, so that net hydrologic or chemical effects on the soils might be small.

8.8.7 Soil and Air Gas Exchange

If the partial pressure of CO_2 in the soil air would rise, and that of O_2 decrease to levels impairing root function, part of the benefits indicated would not materialize. The improved gas exchange with the atmosphere through increased numbers of stable biopores would tend to keep CO_2 and O_2 in the soil at “safe” levels, at least in naturally or artificially well-drained soils. Wetland crops such as rice or jute have their own gas exchange mechanisms and would not be affected, neither would natural wetland vegetation.

8.8.8 Soil Productivity

In subtropical and other subhumid or semiarid areas, the increased productivity and water-use efficiency due to higher CO_2 would tend to increase ground cover, counteracting the effects of higher temperatures. If there would be locally much less rainfall and increasing intra- and interannual variability, these could lead to less dry matter production and hence, in due course, lower soil organic matter contents. The negative effect on soil organic matter contents of a temperature rise might be more than compensated by the greater organic matter supply from vegetation or crops growing more vigorously because of the higher photosynthesis, the greater potential evapotranspiration and the higher water-use efficiency in a high-CO_2 atmosphere. The temperate zone would thus be likely to have the smallest changes in soils, even in poorly buffered ones, directly caused by the effects of global change.

8.8.9 Effect of Climate Change Plant Physiology and Vegetative Intensity

In general, plants grow faster in warmer climates, which could be good news for some farmers, especially in temperate and cold areas. But this applies only up to a point. When it gets too warm, crops tend to mature too early, and under extreme conditions, high temperatures can kill crops. Although different varieties are bred to withstand certain conditions, each crop ultimately has a limited temperature range. Plants are also affected by the amount of carbon dioxide in the atmosphere. Yields of some crops, such as soybeans and wheat, increase with higher levels of carbon dioxide in the atmosphere, while yields of others, such as sugarcane and corn, do not. Unfortunately some pest plants and weeds grow faster and produce more irritant when atmospheric carbon dioxide is higher.

Higher atmospheric CO_2 concentration increases growth rates (Tomer et al. 2014; Bhatia et al. 2013c) and water-use efficiency of crops and natural vegetation in so far as other factors do not become limiting. The higher temperature optima of some plants under increased CO_2 would tend to counteract adverse effects of temperature rise, such as increased nighttime respiration. The shortened growth cycle of a given species because of higher CO_2 and temperature would be compensated for in natural vegetation by adjustments in species composition or dominance. In agroecosystems the choice of longer-duration cultivars or changes in cropping pattern could eliminate unproductive periods that might arise because of the shorter growth cycle of the main crop.

There will be adequate time to adjust to the changes since these are expected to occur over decades, rather than years or days as in all present experimental situations. The increased productivity is generally accompanied by more litter or crop residues, a greater total root mass and root exudation, increased mycorrhizal colonization and activity of other rhizosphere or soil microorganisms, including symbiotic and root-zone N fixers. The latter would have a positive effect on N supply to crops or vegetation. The increased microbial and root activity in the soil would entail higher CO_2 partial pressure in soil air and CO_2 activity in soil water and hence increased rates of plant nutrient release (e.g. K, Mg, micronutrients) from weathering of soil minerals. Similarly, the mycorrhizal activity would lead to better phosphate uptake. These effects would be in synergy with better nutrient uptake by the more intensive root system due to higher atmospheric CO_2 concentration. These changes increase the resilience of the soil against physical degradation and nutrient loss by increased intensity, seasonality or variability of rainfall, as well as against some of the unfavourable changes in rate or direction of soil-forming processes.

The Intergovernmental Panel on Climate Change (IPCC) suggests the following changes in farming practice to take the control of the situation resulting due to change in global climatic conditions:

1. Altering inputs such as varieties/species to those with more appropriate thermal time and vernalization requirements and/or with increased resistance to heat shock and drought, altering fertilizer rates to maintain grain or fruit quality consistent with the prevailing climate, altering amounts and timing of irrigation and other water management
2. Wider use of technologies to “harvest” water, conserve soil moisture (e.g. crop residue retention) and use and transport water more effectively where rainfall decreases
3. Managing water to prevent water logging, erosion and nutrient leaching where rainfall increases
4. Altering the timing or location of cropping activities
5. Diversifying income through altering integration with other farming activities such as livestock raising
6. Improving the effectiveness of pest, disease and weed management practices through wider use of integrated pest and pathogen management, development and use of varieties and species resistant to pests and diseases and maintaining or improving quarantine capabilities and monitoring programs
7. Using climate forecasting to reduce production risk

8.9 Global Climate Change and Soil Horizon

The changes in the soil horizon as affected by the global climate change are being studied throughout the world by the various researchers. The following paragraphs summarize the broader overview of the probable alterations in the soil profile and properties as influenced by the changing climate conditions. These results present case studies in different parts of the world emphasizing the most expected changes in the soil profile properties due to change of climate conditions:

1. The yellowish sandy ferralsols and ferralic arenosols of Eastern Amazonia, Kalimantan and the Zaire basin may rapidly change into podzols or albic arenosols (giant podzols) with even small increases in total rainfall or stronger seasonality, or increased input of acidic (“poor”) organic matter. An increase in effective rainfall due to climate change may cause a major increase in the extent of podzols formed from present-day yellowish sandy ferralsols where, presently, podzols occur in patches within the ferralsol area (Lucas et al. 1987; Dubroeucq and Volkoff 1988).
2. The imperfectly drained loamy Plinthosols on the flat interfluves of Western Amazonia would change into shallow, droughty soils with an irreversibly hardened subsoil if subject to drying out with climate change.

3. The deep reddish, porous loamy to clayey ferralsols of the transition zones between forest and savanna in Eastern Africa, stable under the present vegetation, may be leached so far that a denser subsoil with washed-in clay is formed below an unstable topsoil with little organic matter, as already observed where the land was cleared several decades ago; the same may happen over more extensive areas under a sparser vegetation brought about by a somewhat drier climate.
4. The silty Fluvisols in the broad river valleys of the Sudano-Sahelian zone of West Africa, such as the interior delta of the Niger River, may become saline or sodic upon even minimal change in precipitation and flooding regimes – as exemplified by current human actions with the same soil hydrological implications (Sombroek and Zonneveld 1971).

8.10 Conclusion

Soil quality is the capacity of soils within landscapes to sustain biological productivity, maintain environmental quality and promote plant and animal health, whereas soil health is the condition of the soil in relation to its inherent, or potential, capability to sustain biological productivity, maintain environmental quality and promote plant and animal health.

One major essential component of good soil health is undoubtedly soil organic matter. Organic matter present in soil is vital because it supports many soil processes that are associated with fertility and physical stability of soil across the various ecosystem services. In particular organic matter provides an energy source for microbes; structurally stabilizes soil particles; stores and supplied plant essential nutrients such as nitrogen, phosphorus and sulphur; and provides cation/anion exchange for retention of ions and nutrients. The unanimous approaches to deal with the present scenario of climatic change seem to lie in the ideas of mitigation and adaption. The former approach pays emphasis on decreasing the release of stored carbon and other greenhouse gases. There are opportunities for mitigation in the agricultural sector to help reduce the impact of climate change, and there is significant room for promoting mitigation methods. The adaptation approach on the other hand uses the idea of modification of present agricultural practices as a method to adjust to the erratic climatic pattern.

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9

Organic Agriculture: Potentials in Managing Abiotic Stresses in Crop Production

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Abstract

Organic agriculture is gaining prominence world over, and about 57.8 Mha were organically managed in 2016. Agriculture can contribute to mitigate climate change by (a) reducing emissions of greenhouse gases (GHGs) and (b) by carbon sequestration in the soil. The potential of organic agriculture for both these effects is reported to be high. In organic production systems, the nitrogen input to soils and hence the nitrous oxide emissions are low. Application of organic inputs such as animal manure, compost and green manures increases soil carbon levels substantially. Many field experiments worldwide show that organic fertilization compared to mineral fertilization results in higher soil organic carbon and thus sequesters large amounts of CO_2 from the atmosphere to the soil. Furthermore, soils in organic agriculture capture and store more water than soils of conventional agriculture. Soils under organic agriculture are also less prone to erosion. Hence, organic agriculture production is reported to be more adaptive than conventional agriculture to extreme weather conditions such as drought and flooding.

Keywords

Climate change · Mitigation potential · Adaptation · Organic farming

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9.1 Introduction

Climate change and variability is one of the potential threats to sustainable development of agriculture and food security. Climate change phenomenon is now a global reality. Although climate change is of extreme concern for all countries, India is one of the most vulnerable countries because of both the magnitude and multitude of effects climate change will have on Indian food security. It may further be affected by relentless land degradation, land fragmentation, labour scarcity, over-exploitation of natural resources, etc. Agriculture is a major contributor to emissions of methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2). India's CO_2 emissions have swiftly caught up with the levels of developed countries; however, per capita emissions remain significantly below than those in developed countries. According to the Netherlands Environmental Assessment Agency (2016), the world per capita average levels were 36.20 billion tonnes (4.9 tonnes per capita), while India emitted 2.47 billion tonnes (1.9 tonnes per capita), respectively. According to the Human Development Report, India contributes only 5% of global emissions despite representing 18% of the world's population, but its share is projected to increase to 12% by 2050 in the absence of mitigation policy (UN 2008). GHGs (greenhouse gases) attributed to agriculture by the IPCC include emissions from soils, enteric fermentation (GHG emissions from the digestion process of ruminant animals), rice production, biomass burning and manure management (Smith et al. 2007). There are other 'indirect' sources of GHG emissions that are not accounted for by the IPCC under agriculture such as those generated from land-use changes, use of fossil fuels for mechanization, transport and agrochemical and fertilizer production (IFOAM 2009).

Climate change and variability pose a major threat to farming communities, particularly in India. This threat includes the increase of temperature, extreme weather conditions like floods, heat wave, cold wave, increased water stress and drought. Crop growth, development, water use and yield under normal conditions are largely determined by weather during the growing season. Hence, seasonal variations in weather events pose risks to agricultural systems either due to water constraints (drought) or surplus of water (floods) and erosion. In this regard, soil stability is crucial to store water in the soil profile, resist extreme weather events and minimize soil erosion. Climate change is no longer a distant projection but a contemporary reality demanding immediate attention. These changes will bring new challenges to farmers. Farmers need new technological options to help them adapt to climate change and variability. Organic farming is one such option which is reported to have both climate change mitigation and adaptation potential particularly in rain-fed agriculture.

9.2 Potential of Organic Farming to Mitigate Climate Change

There is considerable worldwide support from results of long-term experiments in advocating organic agriculture for climate change mitigation (Kotschi and Müller-Sämann 2004; Niggli 2007; IFOAM 2008; Goh 2011; Wani et al. 2013). The potential of organic agriculture in climate change mitigation depends on its ability to reduce emissions of GHGs (nitrous oxide, carbon dioxide and methane), increase soil carbon sequestration and enhance effects of organic production technologies which favour the above two processes (Goh 2011).

9.2.1 Reduction of GHG Emissions

The global warming potential of conventional agriculture is strongly affected by the use of mineral nitrogen fertilizers and by high nitrogen concentrations in soils. However, organic farming systems avoid the use of mineral fertilizers and rely on organic inputs such as green manures, crop rotation with legumes, efficient recycling of residues and the use of organic manures. In addition, these systems avoid the use of synthetic/chemical pesticides and rely on practices such as crop rotations, use of biopesticides and beneficial insects for pest management. These restrictions on fossil fuel-based fertilizer and pesticide inputs can significantly reduce the overall GHG footprint of organic agriculture vis-a-vis conventional agriculture (Sreejith and Sherief 2011). Many experimental results suggest that organic agriculture can significantly reduce GHG emissions (Table 9.1).

9.2.1.1 Reduction of Nitrous Oxide (N_2O) Emissions

N_2O emissions are the major source of agricultural emissions accounting for about 38% of agricultural GHG emissions (Smith et al. 2007). The IPCC attributes a default value of 1% to applied fertilizer nitrogen as direct N_2O emissions (Eggleston et al. 2006). Similarly, emission factors of up to 3–5 kg N_2O-N per 100 kg N-input have been reported by Crutzen et al. (2007). These higher values for global N_2O budget are due to the consideration of both direct and indirect emissions, including livestock production, ammonia ($NH_{3)}$ and nitrate ($NO_{3)}$ emissions, nitrogen leakage into rivers and coastal zones, etc. (Scialabba and Lindenlauf 2010). N_2O emissions are directly linked to the concentration of available mineral N (ammonium and nitrate) in soils arising from the nitrification and denitrification of available soil and added fertilizer N (Firestone and Davidson 1989; Wrage et al. 2001). Organic farming involves cover and intercrop which extract plant available nitrogen unused by the preceding crop and keep it to the system reducing the level of reactive nitrogen in the topsoil (Ruser et al. 2001). High emission rates are detected directly after mineral fertilizer additions and are very variable (Bouwman 1995). A study comparing 13 organically and conventionally managed farms showed lower levels of soluble nitrogen in the organically managed soils (Diepeningen et al. 2006).

In organic systems, the nitrogen input to soils and hence the potential nitrous oxide emissions are reduced. The share of reactive nitrogen that is emitted as N_2O

Table 9.1 Direct and indirect reduction on GHG emissions arising from the principles of organic agriculture

1. Agriculture land use and management			
Permanent soil cover	+++	–	+
Reduced soil tillage	+	–	+
Restriction of fallows	+	–	–
Diversification of crop rotations	++	–	+
Restoring the productivity of degraded soil	++	+	–
Agroforestry	++	–	–
2. Use of manure and waste			
Recycling of municipal waste and compost	++	–	+
Biogas from slurry	–	++	–
3. Animal husbandry			
Bedding and keeping for longevity	–	++	+
Restriction of livestock density	–	+	+
Restriction of fodder import	+	+	–
4. Management of fertilizers			
Restrictions of nutrient input	++	–	++
Leguminous plant	+	–	+
Integration of plant and animal production	++	–	+
5. Change of consumer behaviour			
Consumption of regional products	+++	–	–
Shift towards vegetarian products	+	++	–

++ high, + low, – no potential
Source: Adapted from Coleman et al. (1997), Sauerbeck (2001), and FAO (2002)

depends on different soil and weather conditions and management practices, which could partly foil the positive effect of lower nitrogen levels in topsoil (Scialabba and Lindenlauf 2010). In a study by Petersen et al. (2006), lower emission rates for organic compared to conventional agriculture were found for five European countries. However, another study reported no significant differences in N_2O emissions between mineral and organic fertilization (Dambreville et al. 2007). In a long-term study in southern Germany, Flessa et al. (2002) found reduced N_2O emission rates in the organic farm, although yield-related emissions were not reduced. Tuomisto et al. (2012) reported that N_2O emissions were about 30% lower in organic systems than in conventional farming systems.

On the other hand, comparisons between soils receiving manure and synthetic fertilizers found higher N_2O emissions after manure application compared to synthetic fertilizer applications, but not for all soil types (Van Groeningen et al. 2004; Rochette et al. 2008). The higher N_2O emissions after application of manure and plant residues may be due to the higher oxygen demand for decomposition of the organic matter (Flessa and Beese 2000). Furthermore, there are indications that mineral fertilizer applications adversely affect soil organic carbon levels (IFOAM EU 2015). As there is high uncertainty in N_2O emission factors, further research is needed.

9.2.1.2 Reduction of Methane (CH_4) Emissions

The reduction or prevention of CH_4 emissions is of greater importance in global warming from the agricultural sector because two-thirds of global CH_4 emissions are of anthropogenic origin, mainly from enteric ruminant fermentation in animals (FAO 2006) and in rice production (Smith and Conan 2004). Hence, minimization of CH_4 emissions of anthropogenic origin and especially of agricultural origin is of particular importance for mitigation. In general, the CH_4 emissions from ruminants and rice production are reportedly not significantly different between organic and conventional agriculture. Differences are due largely to the extent and intensity of various farming practices and their improvement used within different forms of agriculture.

Although research on CH_4 emissions in organic and conventional paddy rice production is still in its infancy (Goh 2011), employing better rice production techniques such as using low CH_4-emitting varieties (Yagi et al. 1997; Aulakh et al. 2001) composted manures with low C/N ratio (Singh et al. 2003), adjusting the timing of organic input applications (Xu et al. 2000; Cai and Xu 2004) and avoiding continuous flooding have been shown to reduce CH_4 emissions (Smith and Conan 2004). The methods employed for storage and treatment of organic inputs such as manure can also have a very significant effect on GHG emissions. Since composting of manure is used in organic agriculture including biodynamic agriculture, it can reduce N_2O emissions by 50% and CH_4 emissions by 70% (Muller et al. 2016). On the other hand, composting of manure can increase ammonia emissions resulting in 50–120% higher indirect N_2O emissions (Pardo et al. 2015). However, viewed across the whole life cycle from production to application, composting of manure has the potential to reduce the GHG emissions associated with manure management. Further, as herbicides are not used in organic systems, growth of aquatic weeds tends to be higher in organic rice fields, and weeds are reported to have an additional decreasing effect on methane emissions (Inubushi et al. 2001). In organic farming systems, cropping depends on nutrient supply mostly from livestock, and an appropriate combination of cropping and livestock provides an efficient means of minimizing GHG emissions particularly CH_4 (Goh 2011). Efficient and direct recycling of manure and slurry on the farm also helps to reduce GHG emissions as these practices avoid long-distance transport of organic inputs like manures (Niggli 2007).

Methane and N_2O emissions from organic manures account for about 7% of the total GHG emissions from agriculture sector. Methane emissions largely occur in liquid manure systems, whereas higher N_2O emissions occur in solid manure systems and on pastures (Smith et al. 2007). However, there is a very high inconsistency for both CH_4 and N_2O emissions, depending on composition, coverage, temperature and moisture content of the manure. Storing manure in solid form through composting can minimize CH_4 emissions but may lead to more N_2O emissions (Paustian et al. 2004).

9.2.1.3 Reduction of Carbon Dioxide (CO_2) Emissions

Synthetic external inputs like fertilizers and pesticides are not permitted in organic farming. The energy used for the chemical synthesis of nitrogen fertilizers represents up to 0.4–0.6 Gt of CO_2 emissions (EFMA 2005; Williams et al. 2006; FAOSTAT 2009). This is about 10% of direct global emissions from agricultural sector and around 1% of total anthropogenic GHG emissions. CO_2 emissions are reported to be about 40–60% lower in organic agriculture than conventional agriculture, mainly because of non-use of synthetic nitrogen fertilizers which require large amounts of energy in their production and are associated with emissions of the powerful N_2O (Sayre 2003; BFA 2007).

9.3 Soil Carbon Sequestration

Soil carbon sequestration is an important strategy and is a win-win option of producing more food per unit area besides mitigation of climate change (Lal 2004). Although soils of the tropical regions have low carbon sequestration rate because of high temperatures, adoption of appropriate management practices can lead to higher rates particularly in high rainfall regions (Srinivasarao et al. 2012). Soil carbon sequestration at a global scale is considered as the means responsible for the maximum mitigation potential within the agricultural sector, with about 90% contribution to the potential of what is technically feasible (Smith et al. 2007, 2008). However, global soil carbon stocks of agricultural lands have decreased historically and continue to decline (Lal 2004). Hence, improved agronomic practices that lead to less carbon losses or even higher soil carbon storage are necessary (Gattinger et al. 2012).

Soil carbon sequestration can be increased through agricultural management practices like application of organic manures, use of intercrops and green manures, agroforestry systems, perennial grasslands and trees or hedges, etc., which promote greater soil organic matter and soil organic carbon content and improve soil physical properties (Niggli et al. 2008a; Muller 2009). Though organic matter application and cultivation of legume crops are major features of organic farming, crop rotation can also increase soil organic carbon stocks by about 0.8 t CO_2-eq per ha per year, compared to monoculture practices (Muller et al. 2011). There is strong scientific evidence that organic farming generally results in higher soil carbon levels in cultivated soils compared to chemical fertilizer-based agriculture (Table 9.2).Some rough estimates suggest that the global mitigation potential of organic agriculture amounts to 3.5–4.8 Gt CO_2 from carbon sequestration (about 55–80% of total global GHG emissions from agriculture) and a reduction of N_2O by two-thirds (Niggli et al. 2008a). The potential of carbon sequestration rate by organic farming for European agricultural soils has been estimated at 0–0.5 t C per ha per year (Freibauer et al. 2004). IPCC has also indicated increasing soil organic carbon content in agricultural systems as an important mitigation option (IPCC 2007). Similarly, several field studies have confirmed that organic farming practices significantly improve soil carbon pools (Pimentel et al. 2005; Fließbach et al. 2007; Kustermann et al. 2008). In the USA, a field study showed that the carbon sequestration increased by five times in the organic system (1218 kg C per ha per year) as compared with conventional system (Pimentel et al. 2005). Leifeld and Fuhrer (2010) found an average

Table 9.2 Carbon sequestration rates on organic farms

Trial	Variant	Result	References
DOC trial, Switzerland, data for 1978–1998	Biodynamic with composted farmyard manure	Level of soil organic manure remains stable	Fließbach et al. (2007)
		Decrease in soil organic matter: 191 kg per ha compared to the biodynamic variant	
Bavarian organic farms, Germany		Sequestration rates of 110–396 kg per ha and year. Fields managed with integrated pest management: Loss of 249 and 55 kg carbon, respectively	Küstermann et al. (2007)
Rodale experiment, USA	Manure-based organic system	Soil carbon increase 981 kg per ha	Pimentel et al. (2005)
	Legume-based organic system	Soil carbon increase 574 kg per ha	
Nine farming system trials in the USA		Soil organic carbon concentrations 14% higher in organic than in conventional systems	Marriott and Wander (2006)

annual increase of the soil organic carbon (SOC) concentration in organic systems by 2.2%, whereas in conventional systems, SOC did not change significantly. Based on meta-analysis of datasets from 74 studies from pair-wise comparisons of organic vs. nonorganic farming systems, Gattinger et al. (2012) found significant differences and higher values for organically farmed soils of 0.18 ± 0.06% points (mean ± 95% confidence interval) for SOC concentrations, 3.50 ± 1.08 t C per ha for stocks and 0.45 ± 0.21 t C per ha per year for sequestration rates compared with conventional management. Liu et al. (2013) reported soil carbon up to 2–3 times higher in organic matter content and consequent reduction in the carbon emission to the atmosphere. All these studies prove that organic agricultural systems have an inherent potential to both reduce GHG emissions and to enhance carbon sequestration in the soil (Table 9.3).

9.4 Organic Agriculture as an Adaptation Strategy

Adaptation in agriculture is not new. Historically, farmers have developed several methods to adapt to changing climate including aberrant weather. However, the adaptation needs to occur at a much faster rate due to impending climate change. The Intergovernmental Panel on Climate Change (IPPC) defines adaptation to climate change as ‘adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities’ (IPCC 2001). Long-term crop yield stability and the ability to buffer yields through climatic extremes are critical factors in agriculture’s ability to support society in the future (Lotter et al. 2003). Several researchers have reported that

Table 9.3 Potential of organic agriculture to mitigate climate change

Source of GHG	Share of total GHG emissions (%)	Impacts of organic management	Remarks
Direct emissions from agriculture	10–12		
N_2O from soils	4.2	Reduction effect	No synthetic fertilizers are used and higher nitrogen use efficiency
CH_4 from enteric fermentation	3.5	Opposed effect	Reduced by lower replacement rate and multi-use breeds
Biomass burning	1.3	Reduction effect	Burning avoided as per organic standards
Paddy rice	1.2	Opposed effect	Increased by organic amendments but lowered by drainage and aquatic weeds
Manure handling	0.8	Equal effect	Reduced methane emissions but no effect on N_2O emissions
Carbon sequestration			
Arable lands	–	Enhanced effect	Increased soil organic matter
Grasslands	–	Enhanced effect	Increased soil organic matter

Source: Adapted from Scialabba and Lindenlauf (2010)

organic farming systems perform superior than their conventional counterparts during climate extremes including drought and excessive rainfall.

First of all, organic farming is reported to be low-risk farming as it involves reduced input cost, therefore more adaptive to extreme weather events in the wake of climate change and variability (Eyhorn et al. 2007). Organic agriculture systems have a strong potential for building resilient food systems in the face of climate change and variability, through farm diversification and building soil fertility with organic matter (Scialabba and Lindenlauf 2010). Several mechanisms may increase drought or flood tolerance of organic cropping systems. Soil organic matter has positive effects on the water-capturing capacity of the soil. Several studies have shown soil organic carbon to be higher in organically managed systems (Reganold 1995; Clark et al. 1998; Liebig and Doran 1999; Gopinath et al. 2008, 2011). As a result, organically managed soils have high water holding capacity (Liebig and Doran 1999; Wells et al. 2000), and it was observed that water holding capacity of soil's organic plots was twice as high as in conventional plots during torrential rains reducing soil erosion (Lotter et al. 2003). Similarly, Pimentel et al. (2005) reported that the amount of water percolating through the top 36 cm was 15–20% higher in the plots under organic systems compared to conventional systems. The organic soils held 816,000 litres per ha in the upper 15 cm of soil. This was the possible reason for higher yields of corn and soybean particularly in dry years. In India, most of the organic cotton farmers stated that the capacity of their soils to absorb and retain water was increased after conversion to organic management (Eyhorn et al. 2009). Many farmers also said that they needed less rounds of irrigation and the crops could sustain longer periods of drought. In Central America, farmers using organic and sustainable farming methods reported significantly lower economic losses, and 90% of the neighbours of the study farms indicated a desire to adopt their neighbours' methods after observing the environmental stress tolerance of the organic/sustainable farms (Holt-Gimenez 2002). In the 21-year Rodale Farming Systems Trial involving comparison of two organic and a conventional crop rotation, the organic cropping systems performed significantly better in 4 out of 5 years of moderate drought. In the severe drought year of 1999, three out of the four crop comparisons resulted in significantly better yields in the organic systems than the conventional (Lotter et al. 2003). Furthermore, plant's water uptake and ability to withstand moisture stress were significantly improved by mycorrhizal associations (Syliva and Williams 1992). Mycorrhizae have been shown to be more abundant in the roots of crops from organically managed systems compared to those of conventionally managed crops (Eason et al. 1999; Mader et al. 2000). This suggests both a physicochemical and biological basis for the increased drought tolerance of organic cropping systems (Lotter et al. 2003).

The reduction of runoff, soil erosion and crop losses as a result of high-intensity rainfall is also improved in organic farming systems (Lotter et al. 2003). Organic management of soils results in improved soil stability, infiltration, water holding capacity and resistance to water erosion compared to conventionally managed soils, due to higher soil C content and improved soil aggregation (Reganold 1995; Clark et al. 1998; Liebig and Doran 1999), permeability (Reganold et al. 2001) and lower bulk density as well as higher resistance to wind erosion (Jaenicke 1998). Lockeretz et al. (1981) reported that the erosion from Midwest organic farms was one-third less compared to conventional farms. Many studies have also reported that crops under organic management have outyielded conventionally managed crops under flood conditions, due to higher levels of water-stable aggregates in organic soils and associated reduced soil compaction after tillage (Denison 1996; Lotter et al. 2003). Hence, organic production technologies including application of organic manures, green manuring, crop rotation and cultivation of legume crops will be a valuable resource for adaptation to climate change and climatic variability, providing soil and crop characteristics that can better buffer environmental extremes.

Organic farming is reported to have few weaknesses too. The main constraints being reported are low productivity and yield loss in some crops and high dependency on nutrients derived from livestock. Such issues need research. Each country can allot some research budget for this in order to improve the performance and in longer run to have more positive impact on climate change. In spite of these weaknesses, organic agriculture is reported to be the most promising approach for

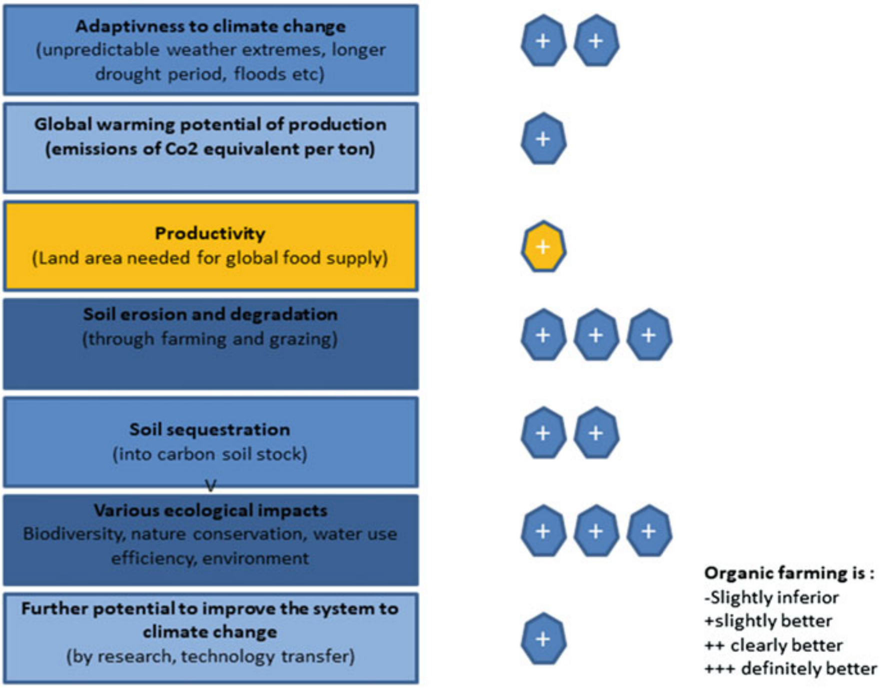

Fig. 9.1 Comparative performance of organic agriculture vis-a-vis conventional agriculture in the context of climate change. (Source: Adapted from Niggli et al. 2008b)

mitigation and adaptation to climate change (Fig. 9.1). It can serve as a benchmark for allocating development resources to climate change adaptation or to measure progress in implementing climate-related multilateral environmental agreements (Niggli et al. 2008b).

9.5 Summary

Organic farming systems have an inherent potential to both mitigate climate change through reduced GHG emissions and higher carbon sequestration in the soil and adapt to climate change through higher soil stability, reduced runoff and erosion. Farming practices such as organic agriculture that lead to improved soil fertility and increase organic matter in soils are better placed to maintain productivity in the event of drought, irregular rainfall events with floods and rising temperatures. Soils in organic agriculture capture and store more water than soils of conventional cultivation. Therefore, organic agriculture is one of the adaptation strategies that can be targeted at improving the livelihoods of rural populations that are especially vulnerable to the adverse effects of climate change and variability.

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Plant-Associated Microbial Interactions in the Soil Environment: Role of Endophytes in Imparting Abiotic Stress Tolerance to Crops

10

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Abstract

Plant-associated microbial interactions involve the great array of root/shoot dynamic environments known as the rhizosphere (in soil) and phyllosphere (plant aerial parts). Here, microbial communities are under multi-prolonged interactions within themselves as well as with plants to improve plant adaptation and tolerance to environmental constraints. Among the different kinds of plant-associated microbial interactions, beneficial "endophytic interactions" occur in rhizosphere as well as in phyllosphere habitats, wherein diverse group of bacterial and fungal communities colonizes plant inter- and intracellular spaces. Structural composition of endophytic microbial communities with respect to few bacterial groups and fungal species has been characterized. Identity of their large diversity and ecological functions of large majority of microbial species in the plant endophytic microbiome are remaining unknown. A variety of distinct abiotic stresses in the soil environment is known to occur singly or in combinations, causing both general and specific detrimental effects on plant growth and development. In addition to the direct negative impact on growth of the plants, abiotic stresses known to affect the rhizosphere soil as well as plant-associated beneficial microbial interactions (symbiotic and endophytic interactions) and thereby crop yield in agriculture. The so-called term induced systemic tolerance (IST) has been put forward to explain different possible mechanisms exerted by the rhizo-/endophytic bacterial and fungal- or microbe-mediated systemic tolerance against abiotic stresses in plants. Hence, there is a necessity for redefining as well as

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rethinking of modern agronomic practices with our current perceptive of the significance of plant-associated beneficial microbial communities (rhizosphere, symbiotic, and endophytic interactions) for plant productivity and health under abiotically stressed environments. In this present chapter, we converse the impact of abiotic stresses upon soil and plant-microbial beneficial interactions; diversity exists in the endophytic microbial interactions (rhizobacterial endophytes, Archaea, fungal endophytes, and beneficial viruses) and their possible mechanisms including habitat-adapted symbiosis involved in promoting growth, development, and tolerance to abiotic stresses in crop plants.

Keywords
Plant microbiome · Plant · Microbe interactions · Endophytes · Stress tolerance · Abiotic stresses

10.1 Introduction

Growth of crop plants is under the influence of various complexities occurring in the soil environmental systems. These complexities are mainly determined as a result of various interactions which are numerous and dynamic in nature. These diverse interactions happen among the components of soil including physical, chemical, and biological, as adapted by the changes occurring in prevailing environmental conditions (Buscot and Varma 2005). Among the different components of soil, the vast guilds of microbial populations have a unique genetic potential as well as varied functional activities. Microbial interactions have a significant impact on soil functions and plant growth (Lynch 1990). Because of the fact that microbes are the major driving force for many soil fundamental metabolic processes which involve specific enzyme activities (Nannipieri et al. 2003). The important environmental processes like biogeochemical cycling, mineralization and immobilization of nutrients, maintenance of plant health and soil quality, etc. are regulated by microbial interactions specifically by their chemical molecules which elicit signals (Pace 1997; Nannipieri et al. 2003; Barea et al. 2004). Many studies have confirmed that root-soil interface is the site where soil microorganisms interact with plant roots and soil constituents (Lynch 1990; Linderman 1992; Glick 1995; Kennedy 1998; Bowen and Rovira 1999). These interactions by root-soil and microbes resulted in the development of an active area/zone known as the rhizosphere, where the microbial communities also interact with each other (Kennedy 1998; Bowen and Rovira 1999). Diverse and metabolically active microorganisms exist in the rhizosphere soil as compared to bulk soil. This is mainly due to the changes in physical, chemical, and biological quality of the root-associated soil (Kennedy 1998; Nannipieri et al. 2003; Barea et al. 2004).

Environmental constraints play a major role in the distribution of plant species across different types of environments and represent the most limiting factors for agricultural productivity. Apart from biotic stresses caused by insects, soil nematodes, plant pathogens, and parasitic plants, there is a variety of distinct abiotic stresses such as water and nutrient deficiency, soil salinity/ alkalinity, and heavy metal toxicity, which occur singly or in combination, causing both general and specific detrimental impact on growth and development of plants and finally reduction in crop yield (ICAR-NIASM Annual report, 2010, 2011). In addition to genetic makeup and physiological adaptations of the plants exposed to stresses, the tolerance of crop plants to above abiotic stress has been observed to be dependent partly on interactions with diverse metabolic activities of rhizosphere-colonizing microorganisms belonging to different biotic groups (Govindasamy et al. 2008). Dense population of microbial groups colonizes the root zone otherwise called as rhizosphere of plants due to large availability of organic carbon compounds synthesized in the plant roots as root exudates. The quality and quantity of root exudates and existing soil conditions play an important role in the specificity of these plant-microbe interactions. Likewise the rhizosphere, the aboveground of the plants called phyllosphere also hosts diverse groups of microorganisms. The role of majority of these microbes to the plant or vice versa has not yet been discovered. The study at the metabolome level revealed to some extent that the specific alternation of sugars occurs by the epiphytic leaf colonization by *Sphingomonas melonis*, an organoheterotroph, and *Pseudomonas syringae* pv. tomato, a phytopathogen, but only a slight alteration was reported by *Methylobacterium extorquens*, a methylotroph (Ryffel et al. 2016). Also, arginine metabolism and phytoalexins biosynthesis was found to be altered in the presence of other commensalistic bacterial interactions (Ryffel et al. 2016). Various plant-associated microbial interactions and their significance in imparting biotic stress resistance and abiotic stress tolerance in plants are given as schematic diagram (Fig. 10.1). In this chapter, we discuss the impact of abiotic stresses on soil and plant-microbial beneficial interactions; diversity exists in the endophytic microbial interactions and their possible mechanisms involved in promoting abiotic stress tolerance in crop plants.

10.2 Abiotic Stresses and Its Impact on Soil and Plant-Microbial Beneficial Interactions

The direct impact of abiotic stresses on soil microbial composition and its function have been studied, and this research area is much focused in recent years (Manzoni et al. 2012; Chen et al. 2014). For example, the relative abundance of soil bacteria and bacterial to fungal ratio of the community in a temperate forest soil is found to be altered by an increase of 5 °C (DeAngelis et al. 2015). Unlike other biological systems, microbial communities respond quickly to warming and other perturbations through resistance. As soon as the stress has been removed, the microbial community returns to an initial/original composition and this is enabled by microbial trait plasticity or its resilience (Allison and Martiny 2008; DeAngelis et al. 2015). Relative shifts in microbial community composition likely lead to changes in ecosystem function when soil organisms differ in their functional traits or control a rate-limiting or fate-controlling step (Schimel and Schaeffer 2012; Chen et al. 2014).

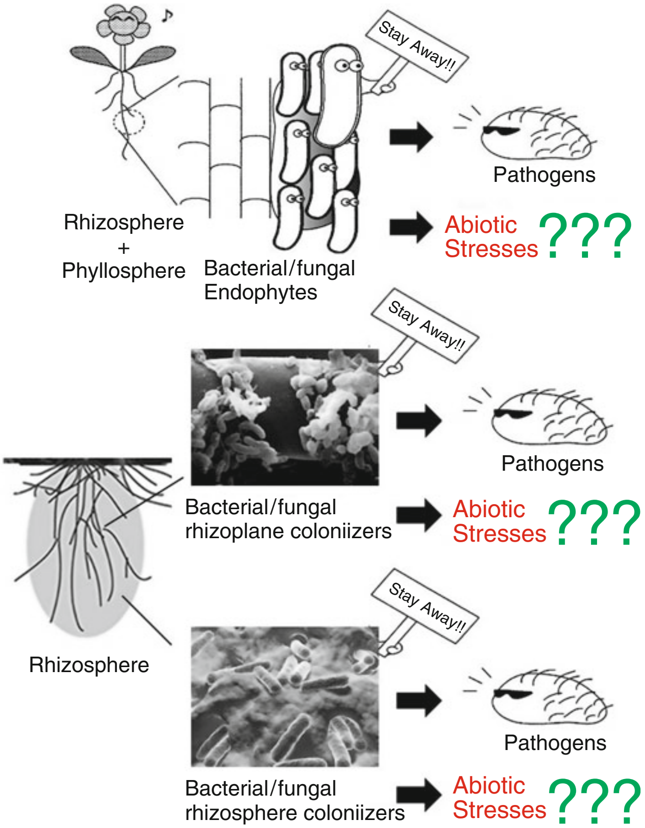

Fig. 10.1 Schematic diagrams showing significance of rhizosphere and phyllosphere microbial interactions imparting biotic stress resistance and abiotic stress tolerance in plants. (Adapted with modifications from Govindasamy et al. 2010)

For example, specific microbial groups regulating ecosystem functions such as nitrogen fixation, nitrification (Isobe et al. 2011), denitrification (Bakken et al. 2012; Salles et al. 2012), and methanogenesis (Bodelier et al. 2000) can have a direct impact on the rate of these processes (Chen et al. 2014). Abiotic stresses like drought and high temperature are directly influencing microbial soil respiration rates because soil microorganisms, and the processes they mediate, are highly sensitive to environmental temperature conditions (Frey et al. 2013; Hagerty et al. 2014; Karhu et al. 2014). The role of elevated temperature conditions on microbial metabolism has received considerable recent attention especially the processes such as decomposition of soil organic matter, soil respiration, and accumulation of soil microbial biomass (Frey et al. 2013; Hagerty et al. 2014; Karhu et al. 2014). In general, increasing soil temperature is coupled with changes in soil moisture conditions, which may explain to some extent for the inconsistent results from experiments exploring how microbial communities respond to climatic change (Zak et al. 1999;

Bell et al. 2008). For example, diversity and rates of microbial activity at increased temperatures can be limited by diffusion and microbial contact with available substrate (Zak et al. 1999). Bacterial communities may respond very rapidly to moisture regimes, while the slower-growing fungal community may lag behind in their response (Bell et al. 2008; Cregger et al. 2012, 2014). Drought situation magnifies the differential temperature sensitivity of fungal and bacterial groups in soil (Briones et al. 2014). For even with small changes in soil moisture availability (<30% reduction in water holding capacity), soil fungal communities may shift from one dominant member/group to another. However, the bacterial communities may remain constant (Briones et al. 2014). These patterns indicate higher fungal than bacterial plasticity during non-extreme conditions of soil wet-dry cycles (Kaisermann et al. 2015). Soil microbial communities which adapted to low soil-water availability or repeated wet-dry cycles in soil may elicit less of a compositional or functional shift to changing water regimes (Evans et al. 2011; Kaisermann et al. 2015). Multiple interactions among microbes, its growing temperature, and moisture regimes in any given location have a high influence on microbial composition and its function. However, there are still many questions on the impact of high temperature and low moisture in soil and their interaction to be answered; Like, how do these affect specific soil microbial functional groups like methanogens within a soil community? What are the effects soil microbial community changes have on microbial functions like decomposition of new and old soil organic matter? Further, which mechanisms drive the net ecosystem response of soil microbial activities to different abiotic stresses?

Similar impacts of changes in beneficial plant-microbial interactions (microorganisms which are known to support plant growth and to increase plant tolerance to biotic and abiotic stresses) will occur due to increased abiotic stress constraints in soil. These microorganisms include plant growth-promoting fungi (PGPF) such as arbuscular mycorrhizae, ectomycorrhizae, and other endophytic fungi; bacteria like rhizobia are involved in legume symbiosis as well as other plant growth-promoting rhizobacteria (PGPR) or plant growth-promoting bacteria (PGPB). Here, the changes in environmental conditions due to abiotic stresses are likely to modify changes in plant physiology and root exudation patterns. One of these stresses like elevated atmospheric CO_2 concentrations particularly in many cases leads to increased carbon allocation to the root zone which may potentially lead to altered composition of root exudates (Haase et al. 2007). These alterations might include changes in the availability of chemotactic attractants or signaling compounds as well as a different C/N ratio or nutrient availability to the rhizosphere beneficial microorganisms (Kandeler et al. 2006; Haase et al. 2008). Relative to aboveground plant structures, soils too have a buffering capacity to changes in temperature and precipitation and possibly to extreme events like frost and others (Durán et al. 2014). Belowground plant-associated microbial communities are, therefore, structured according to changes occurring in the aboveground plant physiology and biochemical mechanisms by different environmental conditions. Increased temperature and drought induce similar changes, and together they are likely to change the composition, abundance, or activity of root-associated microbial communities (Durán et al. 2014). Climate change-induced abiotic stresses may thus substantially impact the diversity of such plant-associated microbial communities, their interactions, and activities (Drigo et al. 2008). As a result, microorganisms known for their beneficial effects on plant growth or health might also be impaired, in terms of exhibiting their desirable properties/traits, colonization capacity, and symbiotic potential under certain environmental conditions. For instance, root symbionts such as rhizobia bacteria and mycorrhizal fungi may impact on plant productivity by altering plant nutrient status. The impact of specific strains of rhizobia on other plant traits may be equally important under abiotic stress conditions. For example, when a common rhizobia strain was present in nitrogen-fixing mutualisms, plant specific leaf area and carbon assimilation rate get increased (Harris et al. 1985). Similar to rhizobia, mycorrhizal fungi exchange nutrients for plant carbon, thus influencing plant carbon to nutrient ratios and subsequently plant productivity (Smith and Read 2008). Specific mycorrhizal strains can alter plant reproduction (Streitwolf-Engel et al. 2001), tiller production, root biomass production, rooting depth, and herbivory rates (Bennett and Bever 2007; Roger et al. 2013). However, the interactions between mycorrhizal strain identity and plant hosts are not always symbiotic and can change with environmental factors or even plant under abiotic stresses (Johnson et al. 1997; Treseder 2004). However, a detailed understanding on how exactly root-associated microbial communities are influenced either directly by altered environmental conditions or indirectly by altered plant physiology due to abiotic stresses and how this affects plant performance and finally ecosystem functioning is still not understood. For this understanding, the main questions lie on how climate change-induced abiotic stresses force to change the direction of plant-root microbe interactions from positive to negative or vice versa and whether climatic change-induced abiotic stresses will change interactions between plants and their myriad of symbionts in tandem, possibly having additive/synergistic effects on ecosystem function. Similar to the impact on symbiotic microorganisms, specific recruitments/selection of endophytic microbial communities and their beneficial interactions with plants growing under altered environmental/ abiotic stress conditions is largely an unknown area of research in plant science.

10.3 Habitats of Endophytes and Their Diversity in Interactions

Microbes can make its own habitat wherever it gets food and protection. It inhabits almost all part of a plant including roots (Govindasamy et al. 2017; Santos et al. 2017), stems (Imazaki and Kadota 2015), leaves (Navarro-Torre et al. 2017; Romero et al. 2014), flowers (Tanapichatsakul et al. 2017), seeds (Shearin et al. 2018), and fruits (Glassner et al. 2015). In addition to these, nodule-forming legumes accommodate some endophytic bacteria (Kong et al. 2017) with the symbiotic rhizobia in the root nodules. De Meyer et al. (2015) termed these endophytes as non-rhizobial root nodule endophytes (NRE). The whole system including plant hosts and its associated endophytic microbiome is termed as holobiont (Zilber-Rosenberg and Rosenberg 2008). The plant-associated microbiome may help the plants to overcome the challenges they face to acquire sufficient nutrients from a given site, defend against herbivores and pathogens, and manage abiotic stresses including drought, salinity, and pollutants (Doty 2017). The plant parts can be divided into aboveground and belowground portions. The aboveground plant portions which act as habitat for microorganisms collectively called phyllosphere include stems (caulosphere), leaves (phylloplane), flowers (anthosphere), and fruits (carposphere). The belowground portions comprise the rhizosphere and rhizoplane area. It is possible that a microbe can originally colonize a part of the plant such as roots and then translocates to other internal plant tissues such as stems and leaves and vice versa in the natural habitat (Chen et al. 2017). All of the three domains of life, viz., Bacteria, Archaea, and Eukarya, are reported to form endophytic association with different plant portions under different climatic conditions and provide protection to the plants from various abiotic stresses.

10.3.1 Rhizobacteria and Bacterial Endophytes

As compared to soil fungi, bacteria inhabiting the rhizosphere called rhizobacteria respond well to root exudates toward nutrient acquisition, and their metabolic activities tend to modulate beneficially the plant growth and development. Root zone bacteria that are found to have beneficial effects on various plants include species of the genera *Pseudomonas*, *Bacillus*, *Enterobacter*, *Serratia*, *Arthrobacter*, *Azotobacter*, *Azospirillum* (Gray and Smith 2005), and *Streptomyces* (Tokala et al. 2002; Dimkpa et al. 2008, 2009). Many of these rhizobacteria colonizing the root surroundings and the surface of the root (exo-root) also penetrate into the root cortex (endo-root) and have been found to possess plant growth-promoting properties as endophytes (Kloepper and Beauchamp 1992; Sessitsch et al. 2004; Long et al. 2008). *Bacillus*, *Pseudomonas*, *Enterobacter*, *Klebsiella*, *Serratia*, and *Streptomyces* are some of the major genera of endophytic bacteria from different crop plants. In a sequence-based study conducted by Hardoim et al. (2015), endophytic bacteria belonged to *Proteobacteria* (54%), *Actinobacteria* (20%), *Firmicutes* (16%), and *Bacteroidetes* (6%). They also reported the presence of endophytic *Archaea* as endophytes based on their meta-analysis. Another study based on 16S-rRNA pyrosequencing demonstrated that the major part (90%) of the endophytic bacterial communities in tomato leaves (*Solanum lycopersicum*) were *Proteobacteria*, followed by other phyla like *Actinobacteria* (1.5%), *Planctomycetes* (1.4%), *Verrucomicrobia* (1.1%), and *Acidobacteria* (0.5%) (Romero et al. 2014). Partial 16S rRNA gene sequencing of non-rhizobial root nodule endophytes isolated from indigenous and exotic legume plants in Flanders (Belgium) revealed a large diversity of different taxa from the classes *Alphaproteobacteria*, *Betaproteobacteria*, *Gammaproteobacteria*, *Actinobacteria*, *Firmibacteria*, *Flavobacteria*, and *Sphingobacteria* (De Meyer et al. 2015). Cultivation-independent approach like fluorescence in situ hybridization technique revealed the presence of endophytes comprising *Proteobacteria (alpha*, *beta*, *gamma)*, *Firmicutes*, and *Actinobacteria* in fruits of *Cucumis melo* (Glassner et al. 2015). Phylogenetic analyses of 73 putative endophytes isolated from Marama bean seed were assigned into 14 phyla including *Proteobacteria*, *Firmicutes*, *Actinobacteria*, and *Bacteroidetes* (Chimwamurombe et al. 2016). Recently, we isolated root endophytes from drought-tolerant cultivars of sorghum (*Sorghum bicolor* L. Moench) and found them in different phylogenetic groups, viz., *α-proteobacteria*, *γ-proteobacteria*, *Firmicutes*, and *Actinobacteria*, which were widespread in sorghum endorhizosphere with the dominance of phylum *Firmicutes* (Govindasamy et al. 2017). *Gammaproteobacteria* and *Firmicutes* were located inside the grapevine epidermis, xylem of ovary, flower ovules, and berries as well (Compant et al. 2011).

Proteobacteria Proteobacteria is the largest and most diverse group of bacteria and thought to have arisen from a common phylogenetic ancestor. It is divided into five classes *α*-, *β*-, *γ*-, *δ*-, and *ε-proteobacteria*. In the earlier reports, the phylum *Proteobacteria* includes *α*-, *β*-, and *γ-proteobacteria*, having the most number of endophytic populations in plants. The well-known symbiont of plants, root nodule-forming bacteria (rhizobia), belongs to the class of *α- proteobacteria* of this phylum. In addition to the symbiotic rhizobia, legumes have an inherent ability to contain endophytic bacteria within the root nodules. Both the host and the rhizobium have been found to contribute in accommodating endophyte in nodules and form mixed colonized nodules in *Lotus japonicus* (Zgadzaj et al. 2015). *Mesorhizobium loti*, the natural symbiont of *Lotus*, selectively guided the endophytic bacteria which belonged to *β-proteobacteria* (*Herbaspirillum frisingense* GSF30 and *Herbaspirillum* sp. B501) toward the nodule primordia through infection thread. Both the strains then multiply and colonize the nodule together with the nitrogen-fixing symbiotic partner (Zgadzaj et al. 2015). Another plant growth-promoting nodule endophyte *Pseudomonas* isolated from *Medicago lupulina* nodules is found to be effective on growth, nodulation, and metal uptake under copper stress (Kong et al. 2017). Co-inoculation of *Mesorhizobium lupulina* with *Sinorhizobium meliloti* and *Pseudomonas brassicacearum* Zy-2-1 improved plant growth, nitrogen nutrition, and metal extraction potential. The proteobacterial genera of *Rhizobium* (α), *Massilia* (β), *Kosakonia* (γ), *Pseudorhodoferax* (β), *Caulobacter* (α), *Pantoea* (γ), *Sphingomonas* (α), *Burkholderia* (β), and *Methylobacterium* (α) were isolated and identified in the Marama bean seeds (Chimwamurombe et al. 2016). *Pseudomonas* (γ), *Variovorax* (β), *Rhizobium* (α), and *Caulobacter* (α) that belonged to *Proteobacteria* were detected in the roots of *Lavandula dentata* (Pereira et al. 2016). Also, the presence of *Pseudomonas* and *Xanthomonas* (γ) were confirmed in the shoots of the same plant. De Meyer et al. (2015) isolated and identified many root nodule endophytes, viz., *Ancylobacter, Bosea, Caulobacter, Inquilinus, Novosphingobium, Paracoccus, Phyllobacterium*, and *Sphingomonas* belonging to *α-proteobacteria*; *Herbaspirillum, Massilia, Roseateles*, and *Variovorax* of *β-proteobacteria*; and *Acinetobacter, Buttiauxella, Enhydrobacter, Erwinia, Pantoea, Pseudomonas, Rahnella, Stenotrophomonas*, and *Xanthomonas* of *γ-proteobacteria*. All these studies indicate the endophytic population of proteobacteria were restricted to the classes *α*-, *β*-, and *γ-proteobacteria*. There is an exception that *Desulfovibrio* and *Geobacter* from the class *δ-proteobacteria* with diverse metabolic traits were reported from flooded rice roots based on *nif* H libraries obtained by cloning and 454 pyrosequencing studies (Ferrando and Fernandez Scavino 2015).

Firmicutes Firmicutes (means strong skin) are phylum of bacteria with low G + C content and gram-positive cell wall structures. Many of them are endospore producers and are resistant to desiccation and can grow and survive under extreme conditions. *Bacillus* is the most observed endophytes of the phylum *Firmicutes* in different plant parts (Compant et al. 2011). Zhao et al. 2016 isolated and identified some root endophytes from salt-accumulating halophyte *Salicornia europaea* grown under extreme salinity including *Bacillus endophyticus* and *Bacillus tequilensis* and found to enhance plant growth under saline stress conditions. *Planococcus rifietoensis, Variovorax paradoxus*, *and Arthrobacter agilis* could be re-isolated as other bacterial endophytes from the host plant interior tissues. *Bacillus* spp., the *Firmicutes*, with low G + C content group were located within the berries, intercellular spaces of pulp cells, xylem of pulp, and also inside the parts of seed cell wall (Compant et al. 2011). The endophytic *Firmicutes* including *Bacillus, Brevibacillus, Cohnella, Exigobacterium, Lysinibacillus, Paenibacillus*, and *Staphylococcus* were identified from the root nodule of native legumes (De Meyer et al. 2015). The genus *Bacillus* was found to be the major as well as dominant endophyte in the fruits of Cucurbitaceae (Glassner et al. 2015). *Bacillus* and *Paenibacillus* were detected in the roots and *Bacillus* spp. in the shoots of *Lavandula dentata* plants (Pereira et al. 2016). Effectual colonization of roots and shoots of clover by two *Clostridium* strains was reported. It is shown that *C. botulinum* can colonize in various forms, viz., individual cells, cell clusters, and microcolonies in various locations of clover plants, namely, rhizosphere, lateral roots, and within the root tissue (Zeiller et al. 2015). Clover plants further showed significant growth when it is co-inoculated with the strain 2301 of *C. botulinum* and *Rhizobia* compared to control plants that were inoculated with only *Rhizobia* (Zeiller et al. 2015). Among the *Firmicutes*, diverse *Bacillus* spp. and *Paenibacillus* spp. were reported as potential PGPRs in agriculture for increasing the crop production and management of biotic stresses (Govindasamy et al. 2010). However, there were limited reports on their role in imparting abiotic stress tolerance in crops.

Actinobacteria Actinobacteria commonly referred to as “actinomycetes” are a group of gram-positive bacteria with a high G + C content in their DNA/genome. They belong to the phylum *Actinobacteria*, one of the largest phyla within the prokaryotes. The actinobacteria represent a large portion of the rhizospheric microbial soil community. Endophytic lifestyle is found to be distributed in a number of actinobacterial genera (other than *Frankia*) within the class 1. *Actinobacteria* belong to the phylum XXVI: the *Actinobacteria* (Govindasamy et al. 2014). This phylum comprises 6 classes, 23 orders, 50 families, and 221 genera (Bergey’s manual of systematic bacteriology, Volume 5, Part A; second edition, 2012). Recent studies have revealed a diverse group of actinobacterial species with multiple functions from various plant species as endophytes. In general, *Streptomyces* spp. were reported as the most predominant species of *Actinobacteria*. *Arthrobacter*, *Microbispora*, *Micromonospora*, *Nocardioides*, *Nocardia*, *Actinomyces*, and *Streptosporangium* are other common genera of endophytic *Actinobacteria* isolated from different terrestrial plants. Recent reports showed the endophytic lifestyle in many rare genera of known description and also nine more new actinobacterial genera, viz., *Jatrophihabitans, Herbiconiux, Jishengella, Koreibacter, Phytohabitans, Phytomonospora, Flindersiella, Actinophytocola*, and *Allonocardiopsis*, from different ecological niches (Govindasamy et al. 2014). *Actinobacteria* are known to exhibit diverse physiological and metabolic properties, such as production of extracellular enzymes and formation of a wide variety of secondary metabolites. In recent years, endophytic actinobacterial study has received special attention mainly because of their many other plant growth-promoting properties and industrial applications. Endophytic *Actinobacteria* have functional relevance for the plants growing in respective abiotically stressed environments, which is still poorly understood. *Arthrobacter* spp. such as *A. agilis* of the phylum *Actinobacteria* that is commonly found in soil and in the roots of halophyte *Salicornia europaea* have grown under extreme salinity (Zhao et al. 2016). All species in this genus are gram-positive obligate aerobes that are rods during exponential growth and cocci in their stationary phase. *Actinobacteria* isolated from the surface-sterilized nodules of different legumes were related to *Actinoplanes, Aeromicrobium, Arthrobacter, Brevibacterium, Corynebacterium, Curtobacterium, Kocuria, Leifsonia, Microbacterium, Moraxella, Mycobacterium, Oerskovia, Plantibacter, Promicromonospora, Rhodococcus, Schumanella*, and *Streptomyces* (De meyer et al. 2015).

10.3.2 Archaeal Endophytes

Archaea, unique domain under prokaryotes, were initially classified as bacteria, hence receiving the name archaebacteria. Archaeal cells have unique properties separating them from the other two domains of biological life forms, Bacteria and Eukaryota (Bergey's manual of systematic bacteriology, Volume 1, second edition, 2001). The recent prokaryotic classification systems aim to organize archaea into groups of organisms that share structural features and common ancestors. These classifications mainly rely on the use of the sequence of ribosomal RNA genes to reveal evolutionary relationships between organisms called molecular phylogenetic system. Most of the laboratory culture-based and well-investigated species of archaea belong to the members of two main phyla, the *Euryarchaeota* and *Crenarchaeota*. Other groups have been tentatively created (Bergey's manual of systematic bacteriology, Volume 1, second edition, 2001), for example, the unusual species called *Nanoarchaeum equitans*, which was discovered in 2003 and has been classified into its own phylum, the *Nanoarchaeota* (Huber et al. 2002). Similarly, a new phylum *Korarchaeota* has also been proposed as separate. It constitutes all small groups of unusual thermophilic species that share features of both of the main phyla but is most closely related to *Crenarchaeota* (Elkins et al. 2008). Many other recently detected species of archaea are only indistinctly related to any of these groups, such as the archaeal Richmond Mine acidophilic nanoorganisms (ARMAN which comprise *Micrarchaeota* and *Parvarchaeota*), which were discovered in 2006 and are some of the smallest organisms known (Baker et al. 2010). A superphylum called TACK has been proposed that includes *Thaumarchaeota*, *Aigarchaeota*, *Crenarchaeota*, and *Korarchaeota* (Guy and Ettema 2011). This superphylum may be related to the eukaryotic of origin. More recently, the superphylum ASGARD has been named and proposed to be more closely related to the original eukaryote and a sister group to TACK (Zaremba-Niedzwiedzka et al. 2017). All these (archaeal) prokaryotic domains are already known for their extremophilic nature. Still the study on archaeal endophytic diversity is very limited. The culture-independent studies by few authors reported the presence of endophytic *Archaea* in some plants, viz., cherries of *Coffea arabica* (Oliveira et al. 2013), roots of *Zea mays* (Chelius and Triplett 2001), and roots, stems, and leaves of the common reed, *Phragmites australis* (Ma et al. 2013). The presence of many archaeal signatures belonging to the phyla *Thaumarchaeota, Crenarchaeota,* and *Euryarchaeota* as endophytic microbial communities from olive leaves was reported recently (Müller et al. 2015). But none of them could be cultivated in laboratory and applied as bio-inoculants into the plants for abiotic stress tolerance studies.

10.3.3 Mycorrhizal Fungi and Endophytic Fungi

The most studied and widespread mutualistic plant-microbe interactions that established by arbuscular mycorrhizal (AM) fungi in the roots of higher plants are still an important topic for the current agricultural and environmental challenges. Almost all (95%) of the terrestrial plants, including most agricultural and horticultural crop species, are able to establish this type of symbiosis with fungi from the phylum *Glomeromycota*. The fungus supplies the autotrophic host with mineral nutrients and water, thereby promoting plant growth. In return, the host plant provides sugar photosynthates to the heterotrophic symbiont. These mutual exchanges, ensuring benefits for both partners, primarily take place at the symbiotic interface between the plant and the fungus, termed arbuscules (Garcia et al. 2016). *Glomeromycota* is one of the eight currently recognized divisions within the kingdom Fungi (Hibbett et al. 2007) with approximately 230 described species. Currently, AMF are divided in 4 orders (*Archaeosporales, Diversisporales, Glomerales,* and *Paraglomerales*), 11 families (*Acaulosporaceae, Ambisporaceae, Archaeosporaceae, Claroideoglomeraceae, Diversisporaceae, Geosiphonaceae, Gigasporaceae, Glomeraceae, Pacisporaceae, Paraglomeraceae*, and *Sacculosporaceae*), 25 genera (*Acaulospora, Ambispora, Archaeospora, Cetraspora, Claroideoglomus, Corymbiglomus, Dentiscutata, Diversispora, Funneliformis, Geosiphon, Gigaspora, Glomus, Intraornatospora, Otospora, Pacispora, Paradentiscutata, Paraglomus, Racocetra, Redeckera, Rhizophagus, Sacculospora, Sclerocystis, Scutellospora, Septoglomus,* and *Tricispora*), and more than 200 species (Oehl et al. 2011).

Another plant beneficial endophytic fungus, *Piriformospora indica*, that belongs to basidiomycete has symbiotic relations with plants similar to that of mycorrhizal symbiosis. *Piriformospora* is a fungal genus belonging to the order *Sebacinales* and family *Sebacinaceae*. It consists of cultivable single genus, containing the single endophytic root-colonizing species *Piriformospora indica*. After its discovery in 1998 from mycorrhizal spores obtained from the rhizosphere of *Prosopis juliflora and Ziziphus nummularia* in the sandy desert soils of Rajasthan, India (Verma et al. 1998), more than hundreds of authors reported its presence and effect in various plants all over the world (Li et al. 2017; Abdelaziz et al. 2017). *P. indica* has proved to be a highly beneficial endophyte with high efficacy in the field. Singhal et al. (2017) in a recent review described the journey of *P. indica* from laboratory to field and finally toward industrialization. A formulation "Rootonic" has been prepared by mixing *P. indica* biomass in magnesium sulfite (raw talcum powder), and the quantity of formulation has been standardized for field trials of various crops.

In addition to the above fungal symbiosis, there are different groups of plant beneficial/mutualistic fungal endophytes that have been identified, which reside entirely within plants, capable of colonizing root, stem, and leaf tissues. Endophytic fungi mainly consist of members of *Ascomycota* or their mitosporic fungi, as well as some taxa of *Basidiomycota*, *Zygomycota*, and *Oomycota* which can produce various bioactive chemicals, promote host growth and resistance to environmental stress, and decompose litter (Sun and Guo 2012). Rodriguez et al. (2009) described different functional groups of endophytic fungi based on their phylogenetic characteristics and life-cycle history traits. Class 1 endophytes are defined as the *clavicipitaceous* endophytes (including *Balansia* spp. and *Epichloë* spp.), and classes 2, 3, and 4 are included in the non-clavicipitaceous types. The diverse class 2 endophytes encompass fungi from *Ascomycota* and a few more fungi belong to *Basidiomycota* (*Dikarya*). The most distinctive feature is their ability to colonize plant roots, stems, and leaves and the formation of extensive plant-fungal infections (Rodriguez et al. 2009). Endophytes from class 3 are extremely diverse and form highly localized infections particularly in aboveground tissues, such as in the leaves of tropical trees, nonvascular and vascular plants (Rodriguez et al. 2009). Class 4 endophytes are also referred to as the dark septate endophytes (DSEs) (Rodriguez et al. 2009). These facultative biotrophic fungi colonize plant roots and have the distinguishing features of having melanized, dark colored, and septate hyphae (Jumpponen and Trappe 1998; Jumpponen 2001). Dark septate endophytes (DSEs), a group of ascomycetous anamorphic fungi, are broadly classified as conidial and sterile septate fungal endophytes with diverse morphological features such as dark septate hyphae and microsclerotia dominantly colonizing root tissues intracellularly and intercellularly from the tropics to arctic and alpine habitats (Jumpponen and Trappe 1998). They have been reported for nearly 600 plant species representing about 320 genera and 100 families (Jumpponen and Trappe 1998). Lugtenberg et al. (2016) recommended an additional class among fungi to recognize the endophytic and entomo-pathogenic fungi as symptomless endophytes of plants that have a unique ability to infect and colonize plants. Marsh bluegrass (*Poa leptocoma*) commonly hosts a vertically transmitted fungal endophyte (*Epichloë* sp.) and naturally grows in wetter conditions than does nodding bluegrass (*Poa reflexa*), which lacks an epichloid endophyte. *Epichloë* is a genus of ascomycete fungi of the family Clavicipitaceae forming an endophytic symbiosis with grasses. Fungal genus *Epichloë* is able to grow in the intercellular space of many different parts, stems, leaves, inflorescences, and seeds of the grass plant without incurring symptoms of disease. Seven genera of fungal endophytes from the flowers of the medicinal plant *Melodorum fruticosum* were identified as *Alternaria, Aspergillus, Colletotrichum, Diaporthe, Fusarium, Greeneria*, and *Nigrospora* (Tanapichatsakul et al. 2017). Endophytic fungal isolates were also identified from the seeds of invasive, non-native *Phragmites australis* that included *Alternaria* spp. representing 54% of all isolates followed by *Phoma* sp. (21%) and *Penicillium corylophilum* (12%) (Shearin et al. 2018). The research study on 310 basidiomycetous endophytes isolated from wild and planted populations of the rubber tree genus, *Hevea*, revealed an unexpected diversity of endophytes including *Bjerkandera*, *Ceriporia*, *Phanerochaete*, *Phlebia*, *Rigidoporus*, *Tinctoporellus*, *Trametes* (*Polyporales*), *Peniophora*, *Stereum* (*Russulales*), and *Coprinellus* (*Agaricales*) in sapwood and leaves (Martin et al. 2015).

10.4 Endophyte-Induced Systemic Tolerance

In addition to nutrient management and plant growth promotion, the systemic abiotic stress tolerance in plants can also be induced by some of these rhizosphere and endorhizosphere colonizing bacterial and fungal species. Similar to induced systemic resistance (ISR) against biotic stresses, the term induced systemic tolerance (IST) has been proposed recently for rhizobacteria-induced physical and chemical changes in plants that result in enhanced tolerance to various abiotic stresses (Yang et al. 2009). Schematic diagram showing different plant habitats of microbial interactions and their corresponding mechanisms involved in induced systemic tolerance (IST) against various abiotic stresses is given in the Fig. 10.2. Recent reports of these mechanisms employed by the rhizobacterial endophytes, endophytic fungi, and beneficial virus interactions in alleviation of various abiotic stresses in plants are listed in Table 10.1.

10.4.1 Possible Mechanisms of IST by Rhizobacterial Endophytes

Some of the possible mechanisms have been speculated for the rhizo-/endophytic bacterial interactions inducing systemic tolerance in plants against abiotic stresses (Fig. 10.3). In general, common adaptation mechanisms of plants showing abiotic stresses, such as water and nutrient deficiency or heavy metal toxicity, comprise changes in root morphology, a process in which plant phytohormones are known to play a key role of defense (Potters et al. 2007). Interestingly, rhizo-/endophytic bacteria can also influence such modifications in root growth by the production of phytohormones such as auxins, cytokinins, gibberellins, abscisic acid (ABA), and ethylene (Stajner et al. 1997; Patten and Glick 1996; Long et al. 2008). For example, the majority of root-associated bacteria have been shown to produce IAA, and

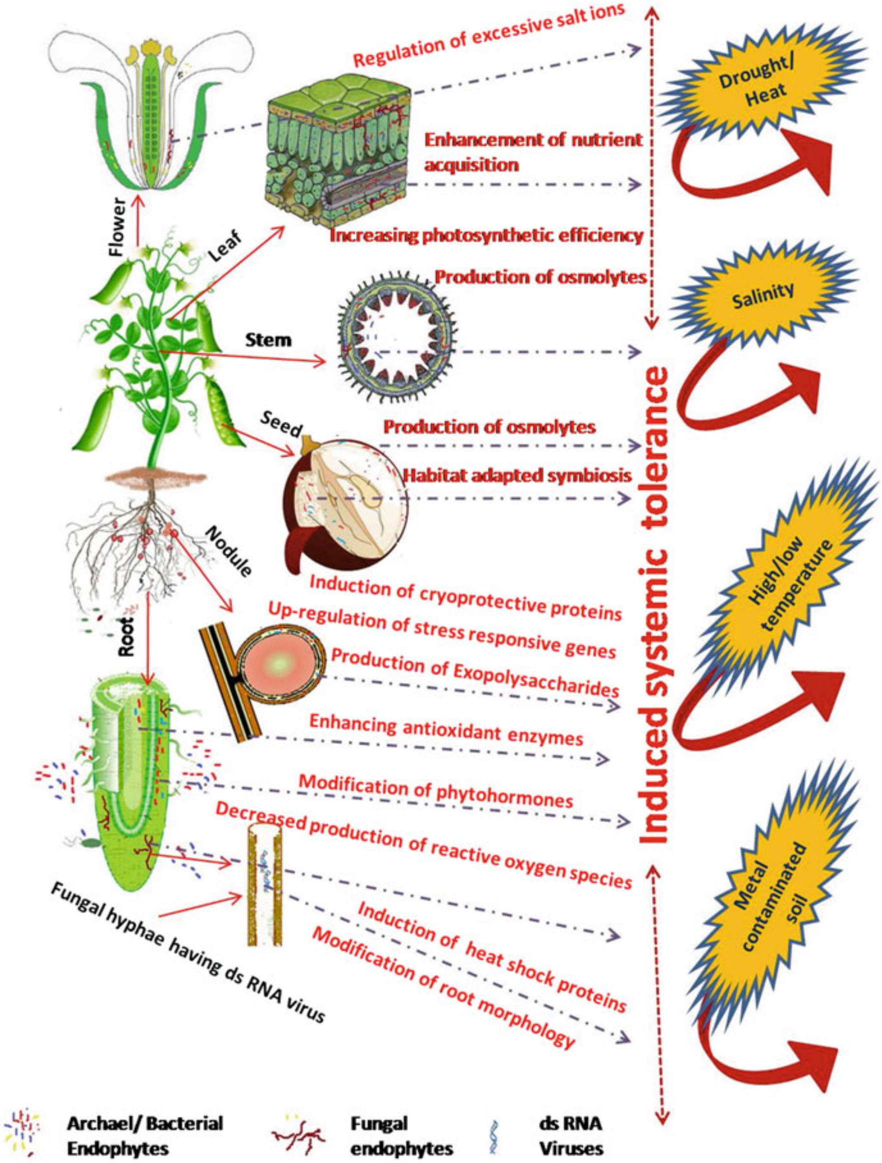

Fig. 10.2 Schematic diagram showing different plant habitats of microbial interactions and their corresponding mechanisms involved in induced systemic tolerance (IST) against various abiotic stresses

inoculation of various plant species with such bacteria has resulted in increased root growth and/or enhanced formation of lateral roots and root hairs (Patten and Glick 1996; Rajkumar et al. 2005; Chakraborty et al. 2006; Long et al. 2008). Increased

Table 10.1 Recent studies highlighting the role of rhizobacterial endophytes, endophytic fungi, and beneficial virus interactions with their possible mechanisms in alleviation of various abiotic stresses in plants

Domain/strain/isolates	Phylum (class/ subclass)	Source of the plant/family	Test crop	Abiotic stress target	Effect of inoculation with the traits possessed by microbes	References
Bacteria						
Pantoea alhagi	Proteobacteria (γ)	Leaves of *Alhagi sparsifolia* (*Leguminosae*)	Wheat (*Triticum aestivum*)	Drought	Osmotolerant and salt-tolerant bacteria; increased accumulation of soluble sugars; decreased accumulation of proline and malondialdehyde (MDA); decreased degradation of chlorophyll in the leaves	Chen et al. (2017)
Sphingomonas sp.	*Proteobacteria* (α)	Leaves of *Tephrosia apollinea* (Papilionaceae)	Tomato (*Solanum lycopersicum*)	Salinity	Regulation of excessive salt ions by activating catalase, peroxidase, and glutathione reductase	Halo et al. (2015)
Burkholderia phytofirmans strain PsJN	*Proteobacteria* (β)	*Glomus vesiculiferum*-infected roots of onion	Maize (*Zea mays*)	Drought	Increased shoot biomass, root biomass, leaf area, leaf relative water content, chlorophyll content, photochemical	Naveed et al. (2014)
Enterobacter sp. FD17	*Proteobacteria* (γ)	Roots of maize				

(continued)

Table 10.1 (continued)

Domain/strain/isolates	Phylum (class/ subclass)	Source of the plant/family	Test crop	Abiotic stress target	Effect of inoculation with the traits possessed by microbes	References
					efficiency of PS-II and photosynthesis	
Enterobacter sp. SA187	*Proteobacteria* (*γ*)	Root nodules of the indigenous desert plant *Indigofera argentea*	*Arabidopsis thaliana*	Salt stress (NaCl)	Different metabolic pathways were identified that potentially contribute to plant growth promotion	Andrés-Barrao et al. (2017)
Pseudomonas azotoformans ASS1	*Proteobacteria* (*γ*)	Leaves of *Alyssum serpyllifolium* grown in serpentine soils	Trifolium grass (*Trifolium arvense)*	Multiple metal (Cu, Zn, and Ni)-contaminated soils under drought stress	Plant growth-promoting (PGP) properties on enhanced chlorophyll content, growth, and Cu, Zn, Ni uptake; enhanced proline and antioxidant enzymes in plants	Ma et al. (2017)
Bacillus subtilis strain B26	*Firmicutes*	Leaves of switch grass cultivar Cave-in-Rock grown under field conditions	*Brachypodium distachyon*	Drought	Upregulation of expression of several drought-responsive genes and the modulation of the DNA methylation process	Gagné-Bourque et al. (2015)

Bacillus spp.	*Firmicutes*	Leaves of the halophyte *Arthrocnemum macrostachyum* growing in saline soils	*Arthrocnemum macrostachyum*	Salt stress	Enhanced plant adaptation, sodium phytoextraction, and restoration of salt-degraded soils	Navarro-Torre et al. (2017)
Pseudomonas brassicacearum Zy-2-1 (co-inoculation with *Sinorhizobium meliloti*)	*Proteobacteria* (*γ*)	Nodules of *Medicago lupulina*	Black medick (*Medicago lupulina*)	Copper (Cu) stress	Capable of producing IAA and siderophores; ACC deaminase activity, with ability to grow in the presence of high concentration of Cu^{2+}	Kong et al. (2017)
Pseudomonas sp. Ps 2–3and *Pseudomonas fluorescens* Ps 7–12	*Proteobacteria* (*γ*)	Rhizosphere soil of Indian mustard	Wheat (*Triticum aestivum*)	Cadmium (Cd) stress	ACC deaminase activity; reduction in the endogenous stress ethylene levels; improved root length and plant growth	Govindasamy et al. (2015)
Sphingomonas sp. pp01, *Pantoea* sp. pp02, *Enterobacter* sp. pp06, and *Bacillus* sp. pp04	*Proteobacteria* (α, γ) and *Firmicutes*	Roots of elephant grass (*Pennisetum purpureum*)	Hybrid *Pennisetum*	Salt stress	Solubilization of insoluble phosphate; fixation of nitrogen; production of indole acetic acid (IAA) and ammonia	Li et al. (2016)
Acinetobacter sp. ACMS25 and *Bacillus* sp. PVMX4	*Proteobacteria* and *Firmicutes*	Roots of *Phyllanthus amarus*	*Medicinal herb (Phyllanthus amarus)*	Salt stress	Promotion of higher vigor index and % germination; increased plant biomass, P content and plant phenolic	Joe et al. (2016)

(continued)

Table 10.1 (continued)

Domain/strain/isolates	Phylum (class/ subclass)	Source of the plant/family	Test crop	Abiotic stress target	Effect of inoculation with the traits possessed by microbes	References
					content; improved radical scavenging and antioxidative activity	
Streptomyces sp. KLBMP 5084	*Actinobacteria*	Halophyte (*Limonium sinense*)	*Limonium sinense*	Salt stress	Significantly lower leaf malondialdehyde (MDA) content and significantly more antioxidant enzymes; lower accumulation of Na^+ in both leaves and roots	Qin et al. (2017)
Fungi						
Trichoderma harzianum TSTh	*Ascomycota*	Roots of dandelion (*Taraxacum officinale*) grown on barren coarse tailings (CT)	Tomato (*Solanum lycopersicum*) and wheat (*Triticum aestivum*)	Nutrient poor and petrochemical-contaminated soils	Increased germination and biomass accumulation; improved plant water use efficiency and drought recovery; secretion of twice the level of peroxidase into CT	Repas et al. (2017)

Exophiala pisciphila GM25 (DSE strain)	*Ascomycota*	Roots	Sorghum (*Sorghum bicolor*)	Drought	Greater plant height, collar diameter, shoot dry weight, net photosynthetic rate (Pn), stomatal conductance (gs), transpiration rate (E), maximal photochemical efficiency of PS-II and photosynthesis	Zhang et al. (2017)
Dark septate fungal endophytes and conidial spores	*Ascomycetes*	Roots of wild rice (*Oryza glumaepatula*) in the Brazilian Amazon	Rice (*Oryza sativa*)	Drought	Decreased oxidative stress and decrease in antioxidant enzyme activity	Santos et al. (2017)
DSE strains (*Phialophora mustea* Pr27, *Leptodontidium* Pr30, *Cadophora* Fe06)	*Ascomycetes*	Trace element (TE)-enriched soils	*Betula pendula* and *Populus tremula x alba*	TE contamination in soil	Decreased lipid peroxidation; increased chlorophyll, K, and P concentrations in the shoots	Berthelot et al. (2017)
DSE strain (*Exophiala pisciphila)*	*Ascomycetes*	Roots	Maize (*Zea mays*)	Soil cadmium stress	Increased the maize growth, kept more cd in roots, and decreased cd content in shoots; improved the photosynthesis and induced notable changes on phytohormones	He et al. (2017)
Systemic (also called class 2) fungal endophytes	–	Plants growing in salinized soil	Tomato (*Solanum lycopersicum*)	Drought and salt stress	Higher root and shoot biomass; better water use efficiency; higher photosynthetic efficiency	Azad and Kaminsky (2016)

(continued)

Table 10.1 (continued)

Domain/strain/isolates	Phylum (class/ subclass)	Source of the plant/family	Test crop	Abiotic stress target	Effect of inoculation with the traits possessed by microbes	References
Cladosporium cladosporioides E-162	*Ascomycetes*	Wild Nicotiana plants growing in arid parts of northern Australia	Tobacco (*Nicotiana benthamiana*)	Drought	Increased shoot length and biomass accumulation	Dastogeer et al. (2017b)
Rhizophagus irregularis strain EEZ 58	*Glomeromycota*	Rhizosphere soil	*Digitaria eriantha* subspecies eriantha	Cold, drought, and salinity	Regulation in the production of antioxidants [high catalase (CAT) and ascorbate peroxidase (APX) activity] and jasmonates [increased endogenous levels of cis-12-oxophytodienoc acid (OPDA), jasmonic acid (JA), and 12-OH-JA]	Pedranzani et al. (2016)
Rhizophagus irregularis strain EEZ 58	*Glomeromycota*	Rhizosphere soil	Tomato (*Solanum lycopersicum*) and lettuce (*Lactuca sativa*)	Drought	Induced strigolactone biosynthesis in plants	Ruiz-Lozano et al. (2016)
Funneliformis mosseae and *Rhizophagus irregularis*	*Glomeromycota*	Rhizosphere soil	*Arundo donax*	Salt stress	Increase in proline accumulation; higher isoprene emission; higher H_2O_2 production	Pollastri et al. (2017)

Rhizophagus irregularis strain EEZ 58	*Glomeromycota*	Rhizosphere soil	Maize (*Zea mays*)	Drought stress	Broader regulation of host plant aquaporins	Quiroga et al. (2017)
Rhizophagus intraradices and *Funneliformis mosseae*	*Glomeromycota*	Rhizosphere soil	*Pelargonium graveolens* L.	Drought stress	Improvement in the growth parameters as well as the phytochemical and physiological characteristics; increased antioxidant activity, total flavonoids, and phenolics	Amiri et al. (2017)
Funneliformis mosseae	*Glomeromycota*	Rhizosphere soil	Trifoliate orange (*Poncirus trifoliata L. Raf.*)	Drought stress	Exhibited significantly higher leaf water potential; modulation of root phytohormones and root morphology	Liu et al. (2016)
Glomus clarum	*Glomeromycota*	Rhizosphere soil	Basil (*Ocimum basilicum* var. *odoratus*)	Salinity	Enhanced the biomass production and accumulation of nutrients, reducing sugars, total soluble carbohydrates, photosynthetic pigments, proline, and protein by reducing Na	Elhindi et al. (2016)

(continued)

Table 10.1 (continued)

Domain/strain/isolates	Phylum (class/ subclass)	Source of the plant/family	Test crop	Abiotic stress target	Effect of inoculation with the traits possessed by microbes	References
Piriformospora indica	*Basidiomycota*	–	Barrel clover (*Medicago truncatula*)	Salinity	Improved antioxidant enzymes activities and hyphae density in roots; reduced malondialdehyde (MDA) activity, Na^+ content and relative electrolyte conductivity (REC); accumulation of proline; upregulation of defense-related genes	Li et al. (2017)
Piriformospora indica	*Basidiomycota*	–	*Arabidopsis thaliana*	Salt stress	Enhanced transcript levels of the genes encoding the high-affinity potassium transporter 1 (HKT1) and the inward-rectifying K+ channels KAT1 and KAT2	Abdelaziz et al. (2017)
Piriformospora indica	*Basidiomycota*	–	Wheat (*Triticum aestivum*)	Drought and mechanical stress	Lower CAT activity and less oxidative damage	Hosseini et al. (2017)

Viruses						
Curvularia thermal tolerance virus (CThTV)	dsRNA fungal viruses	Fungus *Curvularia protuberata* from the plant *Dichanthelium lanuginosum*	*Dichanthelium lanuginosum*	Heat stress	Complex tripartite symbioses and interactions	Marquez et al. (2007)
Brome mosaic virus (BMV), *Cucumber mosaic virus (CMV)*, *Tobacco mosaic virus*, and *Tobacco rattle virus*	ssRNA viruses		Beet (*Beta vulgaris*), pepper (*Capsicum annum*), watermelon (*Cucumis lanatus*), cucumber (*Cucumis sativus*), tomato (*Solanum lycopersicum*), *Solanum habrochaites*, rice (*Oryza sativa*), and zucchini (*Cucurbita pepo*)	Drought	Conditional mutualistic relationships with their plant hosts	Xu et al. (2008)

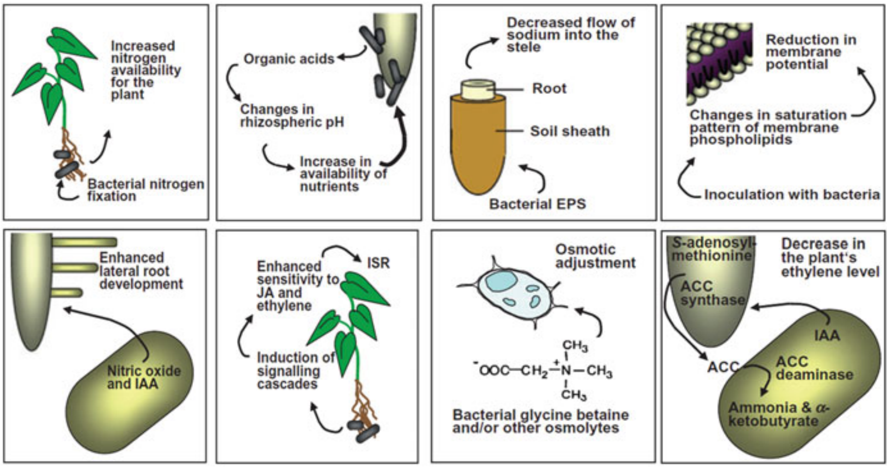

Fig. 10.3 Schematic diagrams showing some of the possible mechanisms of microbial and rhizobacterial endophytes mediated induced systemic tolerance (IST) against abiotic stresses in plants

plant root growth architecture results in a larger root surface, which can, therefore, have positive effects on root water acquisition and plant nutrient uptake under stressful conditions. Some rhizo-/endophytic bacterial strains produce cytokinin and antioxidants, which results in accumulation of abscisic acid (ABA) and degradation of reactive oxygen species leading to oxidative stress tolerance.

Another widespread plant beneficial characteristic found among the endophytic and rhizosphere-colonizing bacteria is ACC deaminase activity. Rhizobacterial species possessing this enzyme can hydrolyze ethylene precursor ACC leading to a decrease in plant interior ethylene hormone level. This in turn resulted in increased root growth architecture (Glick et al. 1998; Burd et al. 2000; Belimov et al. 2007, 2009; Long et al. 2008). Inoculation with ACC deaminase-containing bacteria induces longer roots which might be helpful in the uptake of relatively more water from deep soil under drought stress conditions. Thus, ultimately resulting in increasing water use efficiency of the plants growing under soil water-limited or drought conditions (Zahir et al. 2008). Inoculation of *Achromobacter piechaudii* ARV8 which produced 1-aminocyclopropane-1-carboxylate (ACC) deaminase conferred IST against drought and salt tolerance in pepper and tomato (Mayak et al. 2004). It has been reported that inoculation of rhizobacteria, *Pseudomonas fluorescens* TDK1 possessing ACC deaminase activity enhances the salinity resistance in groundnut by lowering stress-induced ethylene level and showes the significant improvement in root elongation, plant growth parameters, and yield of groundnut (Saravanakumar and Samiyappan 2007). However, decreasing the level of hormone ethylene inside the plants alters the general stress status of the plant under different abiotic stresses, as gaseous hormone ethylene plays a key role in stress-related signal transduction pathways.

Under drought and salinity stress, most of the rhizobacteria and bacterial endophytes induce synthesis of osmoprotectants (such as K+, glutamate, trehalose, proline, glycine betaine, proline betaine, ectoine, etc.) in plants to adjust cytoplasmic osmotic potential through free radical scavenging and subcellular structure stabilization (Talibart et al. 1994). For example, proline synthesis has been shown to be increased in abiotically stressed plants in the presence of beneficial rhizobacteria such as *Burkholderia* (Barka et al. 2006) as well as *Arthrobacter* and *Bacillus* (Chen et al. 2007; Sziderics et al. 2007). Increased production of proline along with decreased electrolyte leakage, maintenance of relative water content of leaves, and selective uptake of K+ ions resulted in salt tolerance in *Zea mays* inoculated with *Rhizobium* and *Pseudomonas* (Bano and Fatima 2009).

Certain rhizobacteria such as *Pseudomonas* survive under drought and nutrient stress conditions by the production of exopolysaccharides (EPS). Exopolysaccharides possess unique water holding and cementing properties and thus play a vital role in the formation and stabilization of soil aggregates and regulation of nutrients and water flow across plant roots. Plants inoculated with exopolysaccharides producing rhizobacteria can display increased resistance to water stress due to improved soil physical structure (Sandhya et al. 2009). Exopolysaccharides can also bind to several cations including Na^+ thus making it unavailable to plants under salt stress conditions.

Under high-temperature conditions, thermotolerant rhizobacteria and thermophilic bacterial endophytes reported to show quick response to a sudden increase in temperature through inducing the synthesis of a specific group of polypeptides known as heat shock proteins (HSPs) (Forrieter and Nover 1998). HSPs consist of molecular chaperons such as GroEL, DnaK, DnaJ, GroES, ClpB, ClpA, ClpX, small heat shock proteins (sHSP), and proteases (Kawashima et al. 2000). These chaperons are involved in the proper folding of denatured proteins. Enzymes like proteases are responsible for the degradation of irreversibly damaged proteins in the cell under high-temperature stress (Martin and Hartl 1997; Munchbach et al. 1999). In addition to their own adaptation to high temperature, few of the reports have shown that thermotolerant rhizobacteria also induce tolerance of plants to high-temperature stress. Plant inoculation of a thermotolerant *Pseudomonas* sp. strain AMK-P6 induces high-temperature tolerance in sorghum seedlings due to synthesis of high molecular weight protein in their leaves. In addition, rhizobacteria also improve plant biomass as well as biochemical status in terms of accumulation of proline, sugar, amino acid, and chlorophyll content (Ali et al. 2009).

Similarly under low-temperature conditions, cold-tolerant bacteria colonizing rhizosphere, rhizoplane, and endorhizosphere show quick response to a decrease in temperature conditions by induced synthesis of cryoprotective proteins (Koda et al. 2001). Inoculation of these bacteria induces cold stress tolerance in crop plants. Cold-tolerant *Serratia marcescens* strain SRM and *Pantoea dispersa* strain 1A display plant growth-promoting characteristics such as IAA production, P-solubilization, HCN, and siderophores production at 15 °C and 4 °C. Seed inoculations with these strains significantly improved biomass and nutrient uptake of wheat seedlings grown in cold temperature conditions (Selvakumar et al. 2008a, b).

10.4.2 IST by Mycorrhizal Symbiosis and Fungal Endophytes

Crop plants are not an exception and respond favorably to external inoculation with arbuscular mycorrhizal (AM) fungi, especially under P deficiency and other abiotic stresses. The arbuscular mycorrhizal (AM) symbiosis is often known to improve plant tolerance to water deficit and drought stress through the modification of plant physiology. AM symbiosis also changes the expression of plant genes in addition to extending the effective root surface area, which is involved in higher water uptake and water circulation. Thus, AM plants generally show an improved ability for nutrient uptake and tolerance against biotic and abiotic stresses especially drought. *Glomus* sp., *Gigaspora* sp., and *Funneliformis* sp. are some of the mycorrhizae frequently used for this kind of studies. There are several reports of AM-induced increase in drought tolerance, involving both increased dehydration and dehydration tolerance in plants. AM fungi inoculation enhances activities of free radical scavenging enzymes such as superoxide dismutases (SOD), peroxidase (POD), and catalase (CAT). This results in improved drought tolerance and osmotic adjustment through improved levels of nonstructural carbohydrates, proline K^+, Ca^+, and Mg^{2+}, consequential in the enhancement of tolerance to salinity (Wu and Xia 2006). Evelin et al. (2009) reviewed the fundamental physiological processes by which AM fungi can improve salt stress tolerance of the host plant. These included enhanced nutrient acquisition (P, N, Mg, and Ca), maintenance of the K^+:Na^+ ratio, biochemical changes (accumulation of proline, betaines, polyamines, carbohydrates, and antioxidants), physiological changes (photosynthetic efficiency, relative permeability, water status, abscisic acid accumulation, nodulation, and nitrogen fixation), molecular changes (the expression of genes: *PIP*, Na^+/H^+ antiporters, *Lsnced*, *Lslea*, and *LsP5CS*), and ultrastructural changes.

AM fungi which can alleviate effects of abiotic stress by improving host plant stress tolerance to drought, salt, and cold was well demonstrated by many authors (Pedranzani et al. 2016; Ruiz-Lozano et al. 2016; Pollastri et al. 2017; Quiroga et al. 2017; Amiri et al. 2017). Millar and Bennett (2016) studied the influence of abiotic stress on AM fungi and proposed the stress exclusion and stress adaptation hypothesis. The "stress exclusion hypothesis" predicts that AM fungal abundance and diversity will decrease with persistent abiotic stress, and the mycorrhizal "stress adaptation hypothesis" predicts that AM fungi will evolve in response to abiotic stress to maintain their fitness. AM fungal communities identified from areas that repeatedly or continuously experience abiotic stress factors such as drought, salinity, heavy metal pollution, nutrient deposition, and extremes of temperature will contain species that are adapted specifically to their environment. These stress adapted AM fungal species may benefit their hosts more under abiotic stress conditions than nonadapted AM fungal ecotypes (Appoloni et al. 2008; Macek et al. 2011). AM symbiosis is shown to favor C and N partitioning in roots, increases C accumulation and N uptake, and leads to greater nitrogen use efficiency in wheat plants grown at elevated CO_2 (Zhu et al. 2016). Classification of mycorrhiza association, structural diversity, and functions and major mechanisms of AMF in plant tolerance to major abiotic stresses including salinity, drought, temperature regimes (cold and heat), nutrient deficiency, and metal/metalloids are recently reviewed in detail by Latef et al. (2016). Recently, results from different research studies suggest that mycorrhizal symbioses act on host plant aquaporins. This alters both plant water relations and plant physiology in order to cope better with stressful environmental conditions such as drought. The fungal aquaporins have been related to water transport in the fungal mycelium to vascular plants in the internal exchange membranes at the symbiotic interface. Indeed, it is generally observed that mycorrhizal plants display higher osmotic and hydrostatic root hydraulic conductance under drought stress conditions. These effects are likely to be the result of the combined action of different aquaporins regulated by the mycorrhizal symbiosis (including PIPs, TIPs, NIPs, and SIPs). Thereby it is influencing the transport of water and, most probably, also of other solutes of physiological importance for the plant growing under drought stress conditions (Ruiz-Lozano and Aroca 2017). However, the symbiotic benefits of AM fungi inducing stress tolerance should be further studied in field conditions with appropriate abiotic stress factors.

Another plant beneficial endophytic fungus, *Piriformospora indica* that belongs to basidiomycete, shown to enhance plant tolerance to various abiotic stresses (Waller et al. 2005). In the model plant *Arabidopsis thaliana*, inoculation of *Piriformospora indica* enhanced the drought tolerance through upregulation of many of the drought stress-related genes in plants (Sheremati et al. 2009). *Piriformospora indica* is also shown inducing salt tolerance through activation of glutathione-ascorbate cycle involved in scavenging reactive oxygen species (ROS) in the inoculated barley plants. Endophytic *P. indica* that imparts abiotic stress tolerance should further be extended from the model plants to crop plants.

Other than mycorrhizal fungi, some endophytic fungi are reported to impart drought tolerance in plants. These fungal endophytes are also known to confer tolerance to different abiotic stressors such as drought, heat, and salt (Rodriguez et al. 2008; Hubbard et al. 2012). Clavicipitaceous fungal endophytes (*Neotyphodium* spp.), which colonize the aerial portion of cool season grasses, are vertically transmitted from parents to offsprings and can increase host tolerance to drought (Kane 2011). The tropical panic grass like *Dichanthelium lanuginosum*, found growing in geothermal soils in Yellowstone National Park, forms a mutualistic symbiotic interaction with the class 2 endophyte called *Curvularia protuberata*, which confers heat stress tolerance (Redman et al. 2002). Another group of endophytic ascomycetes fungi, commonly referred to as “dark septate endophytes” (DSEs), resides in below- and aboveground tissues of their host plants and are transmitted horizontally between host plants and contributes to abiotic stress tolerance either during seed germination (mycovitality) or in mature plants (mycoheterotrophy). A growing body of substantiation suggests that plant root-associated fungi such as dark septate endophytes (DSE) can help plants overcome many biotic and abiotic stresses. Of the greatest interest is by DSE on plant metal tolerance and alleviation capabilities in the metal-contaminated soils (Wang et al. 2016). The positive effects of DSE identified through meta-analysis study were increased total shoot and root biomass and shoot nitrogen (N) and phosphorus contents in various crops. Inoculation with the DSE *Phialocephala fortinii* was found to increase shoot and root biomass, shoot P concentration, and shoot N content by 44–116%, relative to uninoculated controls (Newsham 2011).

Another endophytic fungus *Curvularia protuberate* carries a dsRNA virus, which confers thermal tolerance in host plants and also in inoculated tomato plants (Marquez et al. 2007). Poplar roots were colonized by three isolates belonging to the *Helotiales* (P02, P06), and the *Serendipita vermifera* species (P04) in addition to mycorrhizal fungi were highly tolerant to metals (Cd, Zn, Pb, and Cu), and the species were determined by ITS molecular analyses (Lacercat-Didier et al. 2016). Many fungal endophytes have been shown to confer drought tolerance in a number of crops by improved morphological and biochemical mechanisms such as higher water use efficiency and photosynthetic rate (Azad and Kaminskyj 2016; Repas et al. 2017), decreasing antioxidant enzyme activity (Santos et al. 2017), induction of osmoprotectants or compatible solutes (Dastogeer et al. 2017a), improving the nutritional status and root growth (Malinowski and Belesky 2000), and driving the expression of genes implied in homeostasis (Estrada et al. 2013; Molina-Montenegro et al. 2016). The use of fungal endophytes from different ecosystems currently subjected to severe drought conditions could improve the ecophysiological performance and quantum yield of crops exposed to drought stress. Molina-Montenegro et al. (2016) suggested that the presence of fungal endophytes which was isolated from Antarctic growing plants could minimize the negative effect of drought by enhancing drought tolerance through biochemical mechanisms and improving plant nutritional status. They found that higher net photosynthetic rate and maintenance of higher water use efficiency in endophytes colonized plants under drought conditions. This was often correlated with greater fresh and dry biomass production as well as greater root system development in plants. In addition, the presence of fungal endophytes was linked with a higher proline concentration, lower peroxidation of lipids, and up-/downregulation of ion homeostasis. Adams et al. (2017) reported the novel hypothesis that endophyte symbiosis by fungi *Epihole* promotes host fitness under flooded conditions, thereby contributing to niche differentiation between the two bluegrass species. They provide several benefits to their plant hosts, including the production of different herbivore-deterring alkaloid compounds, increased stress tolerance, and growth promotion.

10.5 Habitat-Adapted Symbiosis and Plant Abiotic Stress Tolerance

Recently, the concept of habitat-adapted symbiosis of bacterial microbiome and fungal endophytes promoting abiotic stress tolerance in host plants has been proposed. The plants growing in many stress environments/habitats have shown to select specific microbiome, and isolated bacterial/fungal endophytes of them reportedly induce abiotic stress tolerance in both host and other crop plants (Redman et al. 2011; Marasco et al. 2012). Rodriguez et al. (2008) for the first time defined this ecological phenomenon as habitat-adapted symbiosis and determined that fungal endophytes (*Fusarium culmorum* as dominant) from coastal and geothermal habitats confer plant habitat-specific stress tolerance. The same fungal species isolated from plants in habitats devoid of salt or heat stress did not confer these stress tolerances. Rodriguez et al. (2005) suggested three important classes of fungal symbionts: (1) the well-studied mycorrhizal fungi, (2) class 1 endophytes, and (3) the lesser defined class 2 endophytes. Studies have shown that class 2 endophytes confer stress tolerance to host plant species. Fungal endophytic association plays a significant role in the survival of at least some plants in high-temperature stress environments (Rodriguez et al. 2004). Coleman-Derr and Tringe (2014) highlighted many of the advantages of fungal symbiont-based approaches. This explained in favor of the broader recognition of crop species as ecological niches for a diverse community of microorganisms that function in concert with their plant hosts and each other to thrive under fluctuating environmental conditions (Coleman-Derr and Tringe 2014). Firstly, many microbial symbionts are frequently capable of conferring stress tolerance to a wide variety of diverse plant hosts. Many plant growth-promoting microorganisms (PGPM) can confer benefits to both monocots and dicot crop species. Secondly, PGPM frequently confers more than one type of abiotic and/or biotic stress tolerance, and thirdly, plant-associated microbial species represent a vast reservoir of genetic information that has coevolved with their plant hosts under natural environmental conditions. The bacterium *Achromobacter piechaudii*, isolated from dry riverbeds of southern Israel, was capable of increasing salt and drought resistance in both pepper and tomato (Mayak et al. 2004). The knowledge about the assemblage of microbiome structure in the continuous different compartments (endosphere, rhizoplane, and rhizosphere) would assist in predicting a subset of core or minimal microbiome structure and thus facilitate synthetic reconstruction of microbial communities, and their functional complementarity contributes to synergistic effects (Qin et al. 2017). It was demonstrated that habitat-adapted symbiosis may be a common non-Darwinian phenomenon in plant biology and is a significant component of plant adaptation to various environmental stresses (Rodriguez et al. 2008). However, many fundamental questions in plant biology with respect to habitat-adapted symbiosis by the bacterial and fungal endophytes need to be investigated in the future.

10.6 Beneficial Viruses and Plant Abiotic Stress Tolerance

Beneficial viruses are defined as viruses that provide a trait to crop plants that increases their value or growth potential or decreases the need for the use of chemical fertilizers or pesticides. These beneficial plant viruses include several acute viruses (*Brome mosaic virus*, family *Bromoviridae*; *Cucumber mosaic virus*, family *Bromoviridae*; *Tobacco rattle virus*, family *Virgaviridae*; and *Tobacco mosaic virus*, family *Virgaviridae*), which confer tolerance to drought and freezing temperatures in several different crops (Roossinck 2011). When plant root zones were heated up to 65 °C, symbiotic plants infected with the endophytes reportedly tolerate and survive more under the heat stress. But separately to grow both, neither the fungus nor the plant alone was capable of growing at a soil temperature above 38 °C (Marquez et al. 2007). This relationship however is more complex as it was discovered that the endophyte harbors a virus in a tripartite mutualistic symbiosis and that the virus is an essential partner for bestowing heat tolerance to host plants, whereas virus-free endophytes were incapable of conferring this trait (Marquez et al. 2007). Much of the research work on beneficial plant viruses and their endophytic interactions which contribute for inducing abiotic stress tolerance in crop plants is still in progress.

10.7 Future Prospects

Plant-associated microbial species with plant growth-promoting capabilities are reported in numerous plant system and characterization of their beneficial role is very important in agriculture as bio-inoculants. A considerable fraction of endophytes isolated from crops appear to have measurable effects on host plant fitness under abiotic stresses or otherwise called environmental stress conditions. Identification of microbial endophytes for different applications has been challenging in the past due to the frequent lack of understanding on plant-host symptoms, localized colonization, intimate integration with plant cellular structures, and lack of cultivability, recent advances in genomic technologies have helped make this process faster and easier. Root-colonizing bacteria (rhizo- and endophytic bacteria/fungi) and fungal species have been shown to mediate the increased tolerance to abiotic stresses in host plants. Future research should be more focused on rhizo-/endophytic bacterial species that are already reported as known species, to be investigated further for their capability to mitigate abiotic stresses in various crops. For example, many *Bacillus* and *Pseudomonas* species are the well-known rhizosphere and endosphere colonizers and have been shown to afford protection against a range of biotic stresses. However, research on *Bacillus*- and *Pseudomonas*-mediated tolerance to abiotic stresses in several crop plants is not fully explored. In addition to this, specific identification and characterization of rhizo-/endophytic bacterial and fungal strains are associated with different abiotic stress tolerant crop plants; rhizo-/endophytic bacterial and fungal strains that have the potential of simultaneously providing cross-protection against multiple stress factors would be highly important.

Substantial research progress has been made in understanding the morphological, physiological, and molecular mechanisms original to bacterially (rhizo- and endophytic bacteria) mediated resistance to biotic stresses than tolerance to abiotic stresses. So, it is essential to investigate in more detail if and how mechanisms triggering IST by rhizobacteria/endophytes including AM fungi and other fungal endophytes will be very helpful in decoding signaling cascades and those leading to improved tolerance against abiotic stresses. Recently defined ecological phenomenon called habitat-adapted symbiosis by the fungal endophytes allows their host plants to establish in high stress environmental habitats.

Viruses are most often studied as pathogens, but many are beneficial to their hosts by providing essential functions and fitness against abiotic stresses. Studies to understand the mechanisms of these beneficial plant-virus interactions are in the beginning stage. Further, investigations of the mechanisms by which these endophytes can confer abiotic stress tolerance to their plant hosts is another avenue for identifying targets for direct manipulation of stress responses in these crops. Current large-scale agricultural systems rely heavily on monoculture cropping systems, in many cases without between-season or crop rotations, which have been shown to lead to the buildup of specialized plant pathogens, increased disease incidence, and decreased yield. Crop diversification, use of specific cover crops, and crop rotations with legumes can be followed to endorse and maintain a beneficial microbiome between growing seasons for important crop species which helps to maintain sustainable productivity in agriculture. Hence, there is a necessity for redefining as well as rethinking of modern agronomic practices with our current perceptives of the significance of plant-associated beneficial microbial communities (rhizosphere, symbiotic and endophytic interactions) for plant productivity and health under abiotically stressed environments.

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Part III

Scientific Approaches for Assessing Stress Impacts on Crops

Field Crop Response to Water Deficit Stress: Assessment Through Crop Models

11

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Abstract

Improving water productivity is a major concern globally and more problematic in arid and semiarid regions. Decision support system based on crop simulation models can be a handy tool for improving water use efficiency. In this chapter, we have described and compared how water stress factor is quantified in seven widely used crop models, viz. DSSAT, APSIM, FAO-AquaCrop, InfoCrop, CropSyst, STICS and WOFOST. In general, these models use either threshold of soil water availability or ratio of actual to potential transpiration approaches as a measure of water stress. Further, the mechanisms by which these models account for effect of water stress on crop phenology, leaf/canopy growth, dry matter production and its partitioning are discussed. The chapter ends with reviews of crop model intercomparison for simulating crop performance under water deficit conditions. Achieving enhanced water use efficiency by optimizing crop water use through crop simulation models is a challenging task. Inaccurate and oversimplified quantification of crop water stress and its effect on growth and development of crop is a major reason for poor performance of current crop models under water-limited environments. However, incorporation of the improved understanding of physiological effects of water deficit stress on crop growth and development in the current crop growth models has the potential to adequately simulate the crop water productivity under water-shortage environments.

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Phenology · Abiotic stress · Simulation · Growth and development · Intercomparison

11.1 Introduction

Global food production is negatively affected by various biotic and abiotic stresses. Agricultural research around the globe is focused to minimize the production losses due to biotic and abiotic stresses, especially in this era of climate change. Abiotic stresses include drought, salinity, elevated temperature, nutrient deficiencies, frost, etc. Among several environmental factors, water is the major factor limiting crop production at global level. Crops experience water stress when the demand for water is not met by the supply through soil (either by rainfall or irrigation). Plenty of literature is available on the effect of crop water stress on growth and yield of different crops across the world. With advances in science, our understanding of crop water stress and processes through which it affects growth and yield of crops has improved.

Advances in crop physiology and molecular biology have enabled us with a better understanding of the processes through which water stress affects crop growth and yield. Another approach to study the crop ecosystem is with the use of crop simulation models. Crop models are widely used to understand the effect of weather parameters, soil properties and crop management practices on yield, yield prediction, irrigation scheduling, etc. Dynamic crop simulation models are process based, and they employ various established theories and processes in the model to simulate the effect of weather, soil and crop components on growth and yield of crops. Different models rely on different concepts of crop water stress to account its effect on crop production. Though it is easy to define crop water stress, accurate quantification of crop water stress and its representation in crop models is still a challenge in cropping system modelling (Anapalli et al. 2008). This chapter is mainly focused on how different crop models account for crop water stress and how they simulate effect of crop water stress on different growth parameters and yield. Differences in the principles followed by different crop models in quantifying crop water stress may result in varied effects on growth parameters and yield, which points out the necessity for having ensemble of crop models for systems modelling.

This chapter will provide an insight into the quantification of crop water stress in seven crop simulation models, viz. DSSAT, APSIM, AquaCrop, WOFOST, CropSyst, InfoCrop and STICS, and simulation of the impact of water stress on growth and yield in these models. The chapter also includes review on comparison of multiple crop modelling studies in simulating effect of crop water stress on growth parameters and yield.

11.2 Physiology of Water Stress on Growth and Development in Crop Plants

Water deficit stress can be defined as a situation in which plant water potential and turgor are reduced enough to interfere with normal functions. A simplified representation of comparative sensitivity of water deficit stress to phenological development (Fig. 11.1) showed that cereals are more sensitive to water deficit at or just before anthesis (Fischer 1973) and it affects yield by reducing the number of grains per ear rather than ear number or grain size. Drought stress at early growth stage causes impaired germination and poor crop stand (Harris et al. 2002). Drought stress occurring during vegetative stage reduces the rate of tiller appearance in cereals, but as a consequence of compensatory response of re-watering, contrasting effects were reported with more number of tillers in barley (Aspinall et al. 1964) and no-tiller in wheat (Armstrong et al. 1996).

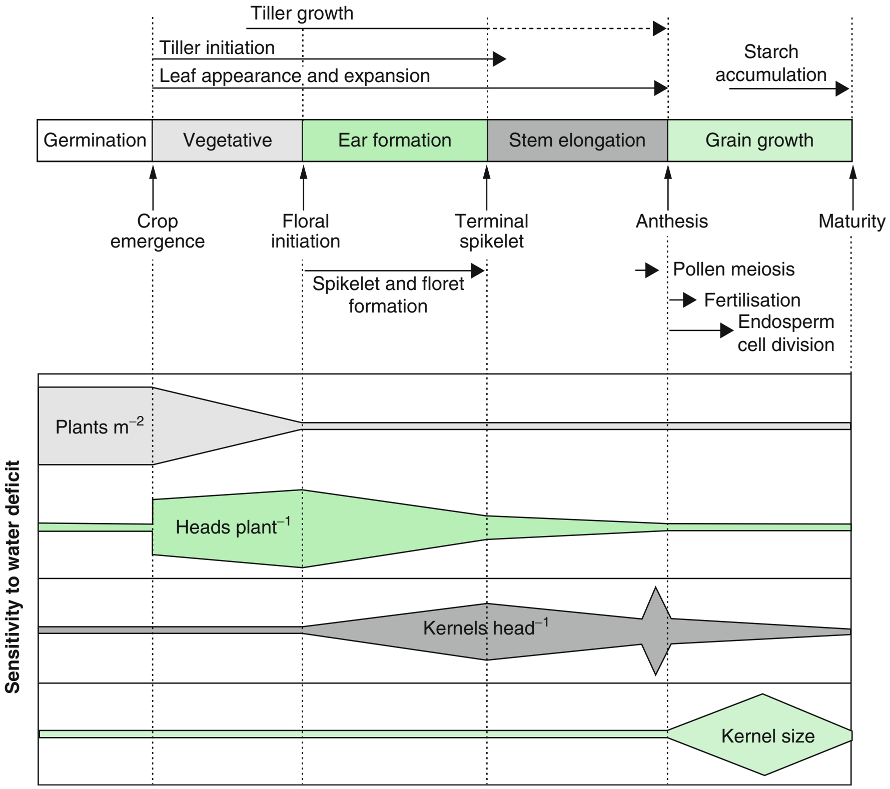


Fig. 11.1 Schematic representation showing relative sensitivity (in terms of bandwidth) of developmental phases to water deficit stress in cereals. (Adopted from Brian et al. 1999)

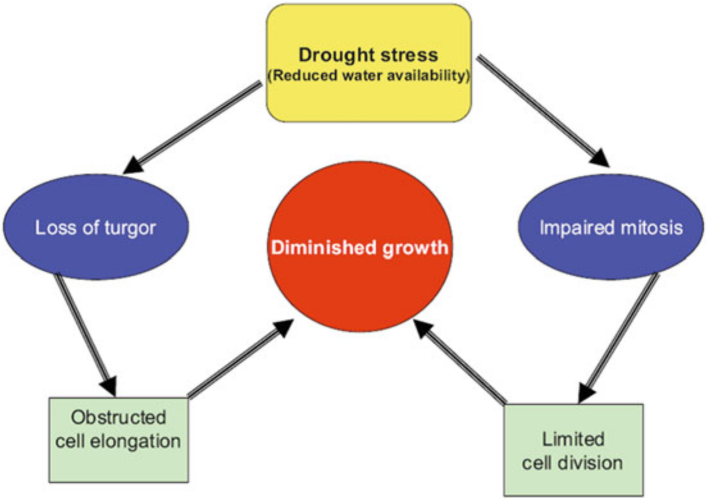


Fig. 11.2 Flow chart explaining possible mechanism of diminished growth under water deficit stress (Adopted from Farooq et al. 2009)

Growth in terms of cell division and cell elongation is one of the most water deficit-sensitive physiological processes caused by reduction in turgor pressure and impaired mitosis (Fig. 11.2). As a consequence, decreased plant height, leaf area and crop growth occur under drought (Hussain et al. 2008, Farooq et al. 2009).

Timing, severity and duration of water deficit stress alter the initiation and length of development phases. Water stress during pre-anthesis in *triticale* genotypes caused reduction in anthesis time, while at post-anthesis it shortened the grain filling period (Estrada-Campuzano et al. 2008). Drought stress during panicle development inhibits the conversion of vegetative to reproductive phase and makes the plants to remain in the vegetative phase until the stress is relieved. Panicle initiation in sorghum was delayed by as many as 2–25 days and flowering by 1–59 days under drought stress, with more severe effects when drought was imposed both at early and late stage of panicle development (Craufurd et al. 1993). In maize, water stress reduced yield by delaying silking, thus increasing the anthesis-to-silking interval. This trait was highly correlated with grain yield, specifically ear and kernel number per plant (Cattivelli et al. 2008). Prevailing drought reduces plant growth and development, leading to hampered flower production and grain filling and thus smaller and fewer grains. A reduction in grain filling occurs due to a reduction in the assimilate partitioning and activities of sucrose and starch synthesis enzymes. Water deficit reduces leaf expansion rates (Barlow 1986). In wheat and maize, drought stress can also reduce the rate of leaf appearance (Abrecht and Carberry 1993, Armstrong et al. 1996). Therefore, stressed crops have lower leaf area indices and intercept less radiation. This is the major reason for reduced crop growth during vegetative growth. Drought stress causes considerable reduction in relative water content, leaf water potential and transpiration rate, with an associated increase in leaf

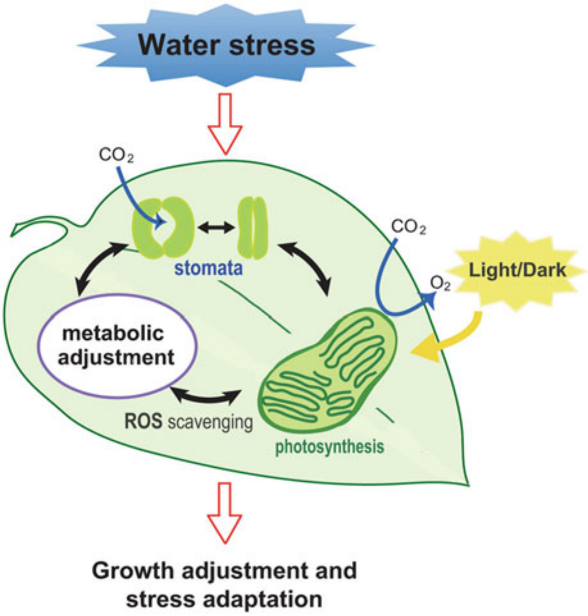


Fig. 11.3 Effect of drought on metabolic adjustment and photosynthesis. (Adapted from Osakabe et al. 2014)

temperature (Siddique et al. 2000). Abbate et al. (2004) reported higher water use efficiency under water deficit stress condition, compared to no-water stress condition in wheat.

Reduction in photosynthesis due to drought is mainly caused by decrease in leaf expansion, damaged photosynthetic machinery, premature leaf senescence and associated decrease in food production (Wahid et al. 2005). Drought induces stomatal closure which limits the CO_2 supply and disturbs the balance between reactive oxygen species and antidefense system causing oxidative stress. These collective responses of water stress cause metabolic changes, reduction in photosynthesis and overall decrease in growth rate of the plant (Fig. 11.3).

Drought stress also alters the assimilate partitioning. Drought stress frequently enhances allocation of dry matter to the roots, which can enhance water uptake (Leport et al. 1999). The rate of export of non-reducing sugar (sucrose) from source to sink organs relies upon the current rate of photo-assimilation and level of sugar in the leaves (Komor 2000). Along with limitation of source, sink strength of reproductive organs is also affected by drought, which regulates the fruit/grain setting (Zinselmeier et al. 1999).

11.3 Water Stress Factor in Different Crop Simulation Models

This section discusses the various approaches by which effect of water stress is accounted in crop simulation models, viz. DSSAT, APSIM, InfoCrop, FAO-AquaCrop, STICS, CropSyst, DAISY and WOFOST.

WOFOST WOFOST stands for WOrld FOod STudies, and it is mainly used for quantitative analysis of growth and production of annual field crops (Boogaard et al. 1998). The water stress factor is included in estimation of actual transpiration rate. The excess or shortage of water in the root zone is measured as soil water content and not as soil water potential (Eitzinger et al. 2004). The transpiration reduction factor (R_{ws}) during water stress period is represented as

$$R_{\mathrm{ws}} = \frac{(\theta_{\mathrm{t}} - \theta_{\mathrm{wp}})}{(\theta_{\mathrm{ws}} - \theta_{\mathrm{wp}})}$$

where 'θ_{t}' is the actual soil moisture content, 'θ_{wp}' is the soil moisture content at permanent wilting point and 'θ_{ws}' is the critical soil moisture content. Critical soil moisture is defined as the soil water content below which root water uptake is affected and the stomata is closed. The value of R_{ws} ranges from zero to one; the lowest water stress is represented by one, and highest water stress is represented by zero.

STICS The STICS model calculates three water stress indices, which acts on transpiration and radiation use efficiency (*swfac*), above-ground growth (*turfac*) (Brisson et al. 2009) and leaf senescence (*senfac*). These water stress indices are fractions ranging between 0 and 1. STICS assumes that the effect of water stress on *swfac*, *turfac* and *senfac* is different.

These three stress indices depend on available water content in the root zone (TETA) according to bilinear laws (Fig. 11.4) and are activated by different

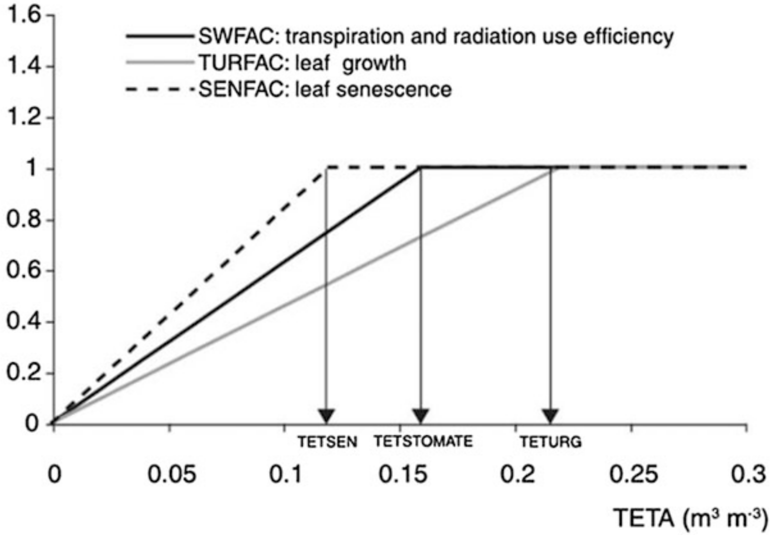


Fig. 11.4 Water stress indices as a function of the available water content in the root zone (TETA). (Adapted from Brisson et al. 2009)

thresholds (TETSTOMATE, TETURG and TETSEN). Brisson et al. (2009) also contains the equations for calculating TURFAC and SWFAC as explained below:

$$\text{if TETA (I)} < \text{TETURG},\ \ \text{TURFAC} = \frac{\text{TETA (I)}}{\text{TETURG}}$$

and

$$\text{if TETA(I)} < \text{TETSTOMATE, SWFAC} = \frac{\text{TETA (I)}}{\text{TETSTOMATE.}}$$

$$\text{if TETA(I)} \geq \text{TETURG, TURFAC} = 1 \quad \text{if TETA(I)} \\ \geq \text{TETSTOMATE, SWFAC} = 1$$

where TETURG is the threshold of TETA below which TURFAC decreases (cm^{-3} cm^{-3}) and TETSTOMATE is the threshold of TETA below which SWFAC decreases (cm^{-3} cm^{-3}).

Effect of water stress on leaf growth is expressed as

$$\text{ll DELTAI} = \left(\frac{\text{DLAIMAX}}{[1 + \text{emp } 5.5(2.2 - \text{ULAI})]}\right) * (\text{TCULT} - \text{TCMIN}) \\ * \min\ (\text{TURFAC},\ \text{INNS})\ \text{EFDENSITE} * \text{DENSITE}$$

where DELTAI is the net leaf growth, DLAIMAX is the maximum rate of setting up of LAI, ULAI is the physiological time unit for calculation of LAI between day of seedling emergence and the first day of maximum LAI, TCULT is the crop temperature (assumed to be the arithmetic mean of maximum crop temperature and minimum crop temperature), TCMIN is the minimum temperature of growth, INNS is the nitrogen stress factor, EFDENSITE is the planting density effect and DENSITE is the plant density.

Effect of water stress on above-ground biomass is represented as

$$\text{DLTAMS} * 100 = \left[\text{EBMAX} * \text{RAINT} - 0.0815 * \text{RAINT}^2\right] \\ * f(\text{TCULT}) * \text{SWFAC} * \text{INNS}$$

where DLTAMS is the daily growth rate, EBMAX is the maximum radiation use efficiency, RAINT is the solar radiation intercepted by the crop, TCULT is explained before, SWFAC is the water stress factor and INNS is the nitrogen stress factor.

FAO AquaCrop FAO has developed AquaCrop model to simulate attainable yield under water-limiting conditions. AquaCrop uses ground cover of canopy in place of leaf area index. The model accounts for effect of water stress on canopy expansion, canopy senescence, stomatal conductance and harvest index. Other crop simulation models discussed in this chapter are mainly focused on effect of water stress on photosynthesis. But AquaCrop has focused on effect of water stress on canopy expansion and senescence. AquaCrop segregates the effect of water stress on canopy cover in to three components, viz. (a) reduction in expansion rate, (b) reduction in stomatal conductance and (c) acceleration of senescence (Steduto et al. 2009). A water stress coefficient (K_s) is used to quantify the effect of water stress, which ranges from one (no stress) to zero (maximum stress). Stress occurs as a result of depletion in relative soil water content of root zone approaching an upper threshold value, p, which ranges between zero and one. When the threshold value is reached, water stress factor (K_s) is computed using the equation (Steduto et al. 2009):

$$K_s = 1 - \frac{\left(e^{D_{\text{rel}} * f_{\text{shape}}} - 1\right)}{\left(e^{f_{\text{shape}}} - 1\right)}$$

where D_{rel} is the relative depletion of root zone soil water content and the parameter f_{shape} influences the shape of the function K_s.

CropSyst CropSyst is a multi-year, multi-crop, daily/hourly time step cropping system simulation model developed to serve as an analytical tool to study the effects of climate, soils and management on cropping systems (Stockle et al. 1994, 2003, 2010). An overall stress index is determined using the following as 'one minus ratio of actual to overall potential biomass growth for each day of the growing season'. Overall potential growth is defined as the growth calculated from potential transpiration substituted for actual transpiration. The overall stress index is divided into different stress indices, viz. light, temperature, water and nitrogen, and their values indicate the plant response to environmental conditions. The value of all these indices ranges from zero to one, where zero denotes no stress and one represents maximum stress.

Water stress factor (SWSF) is defined as (Anapalli et al. 2008):

$$\text{SWSF} = \frac{\text{AT}}{\text{PT}}$$

where AT is the actual transpiration and PT is the potential transpiration.

APSIM Soil deficit factors account for the effects of soil water stress on different plant growth processes. Sensitivity of photosynthesis, phenology, leaf expansion and nitrogen fixation to water stress is accounted by four water deficit factors that are calculated (https://www.apsim.info/Documentation/Model,CropandSoil/CropModuleDocumentation/Plant.aspx).

Water availability ratio is calculated using the following formula:

$$\text{Water availability ratio} = \frac{(\text{sw} - \text{ll})}{(\text{dul} - \text{ll})}$$

where 'sw' is soil moisture content on volume basis, 'll' is equivalent to permanent wilting point, and 'dul' is equivalent to field capacity of soil. The value of stress factor ranges from zero to one, in which zero represents complete stress and one represents no stress.

InfoCrop InfoCrop model is a generic model designed to simulate the effects of weather, soils, agronomic management (including planting, nitrogen, residues and irrigation) and major pests on crop yield and its associated environmental impacts (Aggarwal et al. 2006). It accounts for crop production under water-limited conditions with soil water balance and effect of water stress factors on crop growth and phenology. Water stress factor is defined as

$$\text{Water stress factor} = \frac{\text{Actual water uptake}}{\text{Potential transpiration}}$$

The value of water stress factor ranges from zero (maximum water stress) under depleted soil water conditions to one (no water stress) when actual water uptake is equal to potential transpiration. Aggarwal et al. (2006) have discussed that the effect of water stress during sowing is simulated indirectly by increasing the thermal time, thereby reducing the rate of germination.

DSSAT Decision Support System for Agro-technology Transfer (DSSAT) consists of various crop models executed under a single umbrella (Tsuji et al. 1994). There are two types of crop models, viz. CERES for cereal crops and CROPGRO for legumes. The soil water balance in DSSAT is based on Ritchie's model which uses a one-dimensional 'tipping bucket' soil water balance approach (Ritchie 1972, Ritchie 1981a, b). The fundamental aspect of estimating water stress in DSSAT is the comparison between potential transpiration (demand) and potential root water uptake (plant extractable soil water) (Anapalli et al. 2008). DSSAT accounts for the effect of water stress by two stress factors, viz. TURFAC and SWFAC. Under conditions where water is not a limitation, maximum root water uptake will be higher than potential transpiration. As the soil water content decreases due to uptake, maximum root water uptake decreases. At a critical stage, TURFAC is activated (Fig. 11.5).

TURFAC restricts the expansive growth of crops and is calculated using the formula (Anapalli et al. 2008):

$$\text{TURFAC} = \frac{\text{TRWUP}}{\text{RWUEP1} * \text{EP0}}$$

where TRWUP is potential root water uptake and RWUEP1 is a species-specific parameter which was given a value of 1.5 for all crops included in DSSAT and EP_0 is the potential transpiration. The second stress factor called SWFAC affects crop phenology, growth and biomass-related processes. It is activated when potential transpiration demand equals or exceeds potential root water uptake, and it is defined as

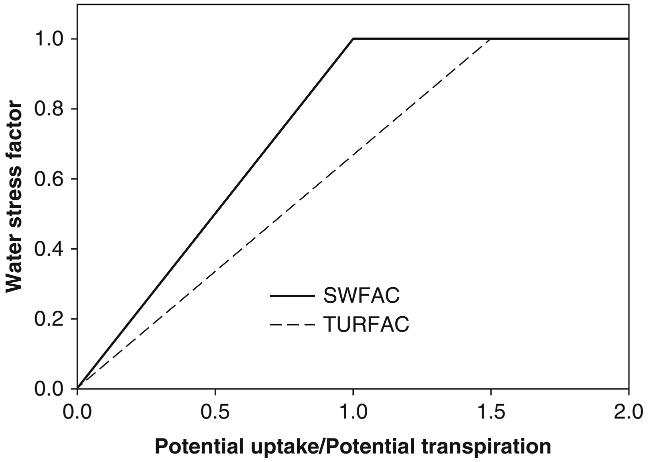


Fig. 11.5 Relationship used to calculate water stress factors TURFAC SWFAC in DSSAT. (Ritchie 1998)

$$\mathrm{SWFAC} = \frac{\mathrm{TRWUP}}{\mathrm{EP0}}$$

The value of both stress factors ranges from zero to one, where one represents no stress and zero represents maximum stress.

11.4 Effect of Water Stress on Plant Growth and Development

This section explains how different crop models simulate the effect of water stress on plant growth and physiological processes like phenology, leaf expansion and canopy growth, dry matter production and its partitioning. This section also discusses the studies on evaluation of different crop models for water-limited condition through practical field experiments.

Parent and Tardieu (2014) divided the current crop models into two classes, i.e. (a) in parallel and (b) in series, for distinguishing the effect of water stress on leaf area and biomass (Fig. 11.6). Models of ‘in parallel’ class simulate the processes independent to each other, but their feedbacks coordinate them. However, models of ‘in series’ class simulate the processes in such a way that one process affects the others via a cascade of events.

11.5 Effect of Water Stress on Phenology

DSSAT In DSSAT-CERES models, phenology of crops is solely influenced by temperature or thermal time, whereas generic CROPGRO module accounts the effect of stresses (water, nitrogen, phosphorus) as a modifier on the basic

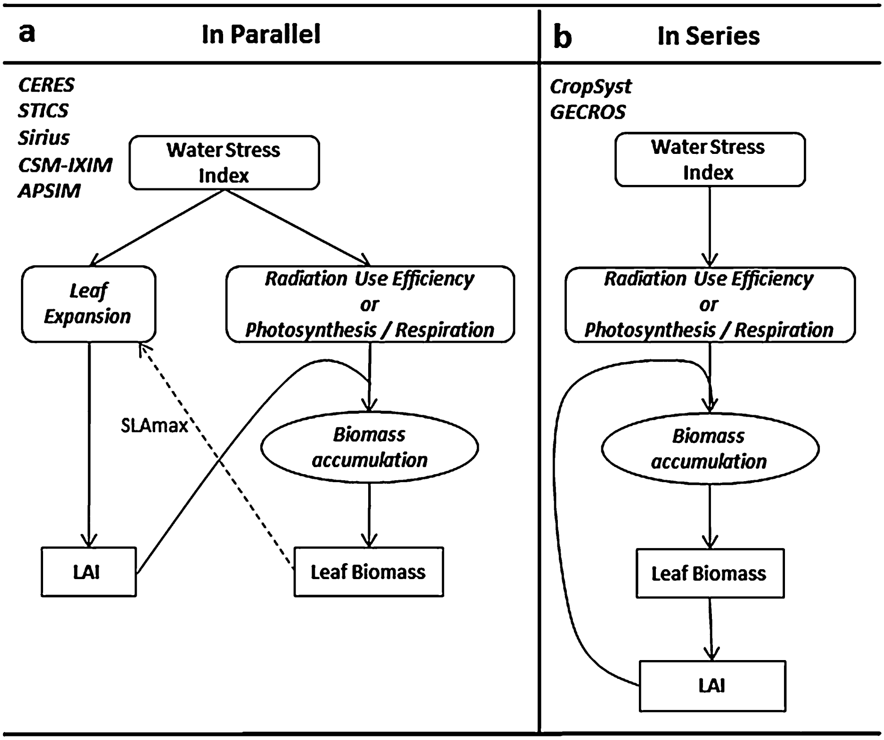


Fig. 11.6 Flowchart explaining the responses to water deficit stress on leaf expansion and biomass accumulation in the two classes of current crop models. (Adapted from Parent and Tardieu 2014)

temperature and photoperiod influence on phenology. During planting to emergence phase, only water content in top 10 cm layer has the influence on phenology. During first development phase, SWFEM function is used as a measure to calculate relative rate modifier for the water stress. SWFEM is a measure of how close soil water is to the field capacity. The value of SWFEM between 20 and 100 would not affect the development progress; it means extreme dry or extreme wet would delay or stop development progress. During later phases, water stress factor for photosynthesis (SWFAC) with a scale factor WSENP (−1 to +1) is used to influence the development progress. When SWFAC is 0.0 (maximum stress), a value of −1.0 WSENP would slow development progress to 0.0, whereas a value of +1.0 WSENP would speed up development progress by a factor of 2.0 (Hoogenboom et al. 2003).

APSIM: Generic Plant Module Between emergence and flowering stages, the calculated 'daily_thermal_time' is moderated by water or nitrogen stresses, causing delayed phenology under stress. Sowing to germination is reliant on soil moisture status only. If seed is sown under sufficient soil moisture condition (specified by pesw_germ), the germination would happen 1 day after sowing (https://www.apsim.info/Documentation/

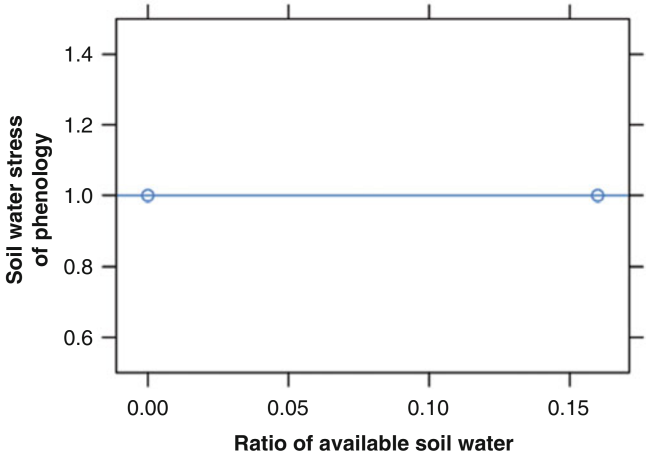


Fig. 11.7 Effect of soil water stress factor on phenology (fW.pheno) and the ratio of available soil water (esw_a/esw_p) in APSIM-wheat. (Source: https://www.apsim.info/Documentation/Model,CropandSoil/CropModule Documentation/Wheat.aspx)

Model,CropandSoil/CropModuleDocumentation/Plant.aspx). For each crop growth stage, simulated daily thermal time (TT') is governed by following expression:

$$\mathrm{TT'} = \sum [\Delta TT * \min(\mathrm{fD}, \mathrm{fV}) * \min(\mathrm{fW.pheno}, \mathrm{fN.pheno}, \mathrm{fP.pheno})]$$

where ΔTT is daily thermal time, fD is photoperiod factor, fV is vernalization factor and fW.pheno, fN.pheno and fP.phenology are water stress factor, nitrogen stress factor and phosphorus stress factor for phenology, respectively.

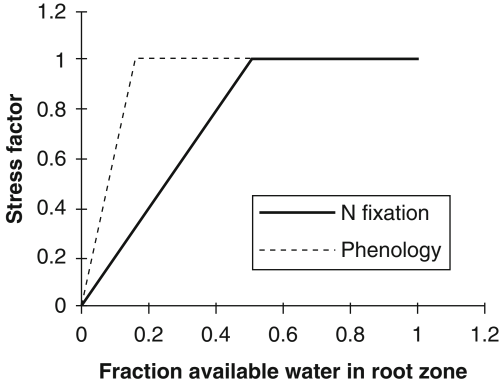
Effect of soil water stress on crop phenology is determined by the soil water stress:

$$f_{\mathrm{w.pheno}} = h_{\mathrm{w.pheno}}\left(\frac{esw_a}{esw_p}\right)$$

where 'esw_a' is the root zone soil water that is actually extractable by plants, 'esw_p' is the root zone soil water that is potentially extractable by plants, and '$h_{\mathrm{w.pheno}}$' is a function of soil water available ratio and soil water stress, which is defined by parameters 'x_sw_avail_ratio' and 'y_swdef_pheno' in '.xml' and linearly interpolated by APSIM. In the current version of APSIM-wheat module, no soil water stress for phenology is applied (Fig. 11.7).

Sensitivity of phenology and nitrogen fixation to water deficit stress is shown in Fig. 11.8. It shows that nitrogen fixation is sensitive to even mild water stress, while phenology is influenced by severe water stress.

Fig. 11.8 Relationship between stress factors for N fixation and crop phenology to the ratio of demand and supply ratio of soil water. (Source: https://www.apsim.info/Documentation/Model,CropandSoil/CropModuleDocumentation/Plant.aspx)



AquaCrop Phenology of crop in AquaCrop is dependent only on user-defined species-specific thermal time. It does not consider the effect of any stresses on phenology (Steduto et al. 2009).

InfoCrop Phenology is calculated by integrating the temperature-driven developmental rates of different phases. During sowing to seedling emergence, water stress delays emergence in many crop plants. The thermal time can be increased depending upon the available water fraction in the surface soil layer. During vegetative and reproductive stages, rate of development is modulated by water and nitrogen stress-dependent temporary function, MAXSTD (Aggarwal et al. 2006).

The rate of development during vegetative stage (DRV) is calculated as

$$\mathrm{DRV} = (\mathrm{HUVG}*\mathrm{DAYLC}*\mathrm{MAXSTD})/\mathrm{TTVG}$$

The rate of development during reproductive stage (DRR) is calculated as

$$\mathrm{DRR} = (\mathrm{AMIN1}(\mathrm{TPOPT}, \mathrm{TPAV}) - \mathrm{TGBD})*\mathrm{MAXSTD}/\mathrm{TTGF}$$

where HUVG is the daily increment in heat units, DAYLC is the day length (photoperiod) correction factor, TPOT is the optimum temperature, TPAV is the daily mean temperature and TTVG and TTGF are the thermal time requirements to complete vegetative and grain filling phases, respectively.

CropSyst Simulation of phenology is based on accumulation of thermal time which is accelerated by water stress. This was conceptualized as canopy temperature increases with the increasing severity of water stress (Stockle et al. 2003).

STICS Emergence of crop depends upon the temperature and water status of seedbed as well as sowing depth. Thermal time in STICS can be calculated by using both air temperature and crop temperature; the latter accounts the effect of water stress on accelerated phenology. STICS also simulate the effect of early stress in delaying the flowering, which is accounted by multiplying maximum of stress factor for water and nitrogen to developmental unit up to onset of filling of harvested organ (DRP) stage (Brisson et al. 2003).

WOFOST Phenological development in WOFOST, which is calculated by thermal time concept and modified by the photoperiod, does not take in to account the effect of water stress on phenological development (Boogaard et al. 2014).

11.6 Effect of Water Stress on Leaf or Canopy Growth

DSSAT Leaf weight growth and specific leaf area are the two parameters which influence the leaf area expansion, and the latter (specific leaf area) is modified by temperature, light and water deficit. In DSSAT-CSM, the turgor factor TURFAC (SWDF2) is initiated after a certain threshold of soil dryness, and it modulates expansive growth (Hoogenboom et al. 2003). Since leaf expansion is more sensitive to water stress compared to photosynthesis or accumulation of dry matter, the crop-specific parameter (RWUEP1) is set as 1.5 which facilitates the decrease in turgor pressure in leaves before reducing photosynthesis (Fig. 11.9).

APSIM: Generic Plant Module Water stress factor for leaf expansion is determined as follows:

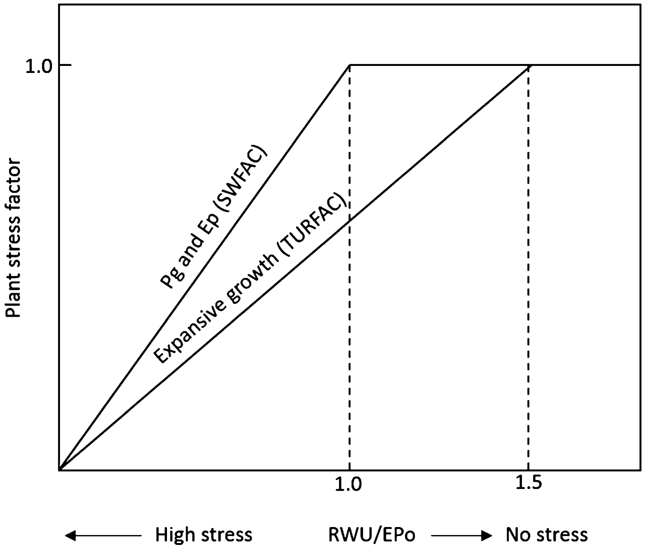


Fig. 11.9 Effect of water stress factors on leaf/canopy growth and photosynthesis in DSSAT

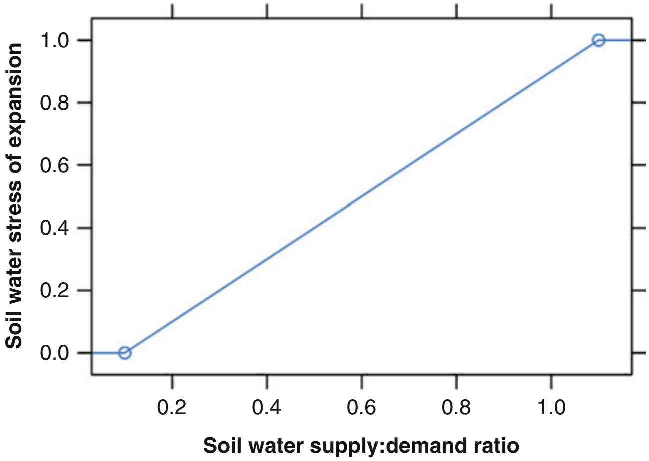


Fig. 11.10 Influence of soil water stress factor on leaf expansion (fW,expan) and soil water supply: demand ratio (We/Wd) in APSIM. (Source: https://www.apsim.info/Documentation/Model,CropandSoil/CropModuleDocumentation/Plant.aspx)

$$f_{\mathrm{W.expan}} = h_{\mathrm{W.expan}}\left(\frac{W_u}{W_d}\right)$$

where 'W_u' is the crop water uptake, 'W_d' is the crop water demand, and '$h_{w.expan}$' is a function of soil water content and stress and is defined by parameters '**x_sw_demand_ratio**' and '**y_swdef_leaf**' in the '.xml', which is linearly interpolated by APSIM (Fig. 11.10).

The relationship between the stress factor for leaf expansion and photosynthesis with water availability ratio is shown in Fig. 11.11. It shows that leaf expansion is more sensitive process to deficit of water stress than photosynthesis.

AquaCrop Canopy growth in AquaCrop is simulated in terms of canopy cover (CC), as it is the most crucial feature of AquaCrop and determines expansion, ageing, conductance and senescence. AquaCrop does not simulate the leaf area index (LAI). It is an established fact that leaf expansion is the most sensitive processes to water deficit stress in comparison to senescence and stomatal conductance (Steduto et al. 2009). The same principle is followed in the AquaCrop model. It can be seen from Fig. 11.12 that lower threshold for leaf expansion (b) is set substantially at p value less than one, while lower threshold for stomatal conductance and senescence is set at p value of one (i.e. at PWP).

During the crop development stage (when CC is between 10% to maximum CC), leaf growth through adjustment of canopy growth coefficient (CGC) is modulated by water stress coefficient of expansive growth (Ks_{exp}) by the following expression:

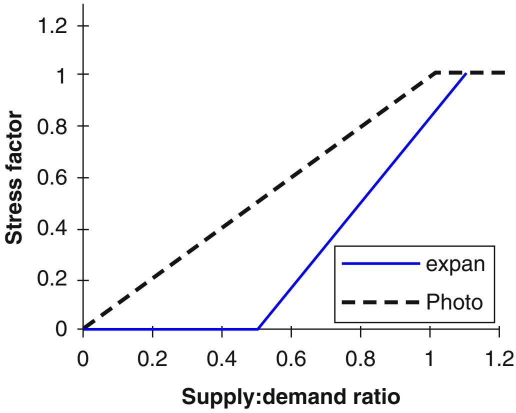


Fig. 11.11 Influence of water stress factors on photosynthesis and leaf expansion to the ratio of demand and supply of soil water. (Source: https://www.apsim.info/Documentation/ModelCropandSoil/CropModuleDocumentation/Plant.aspx)

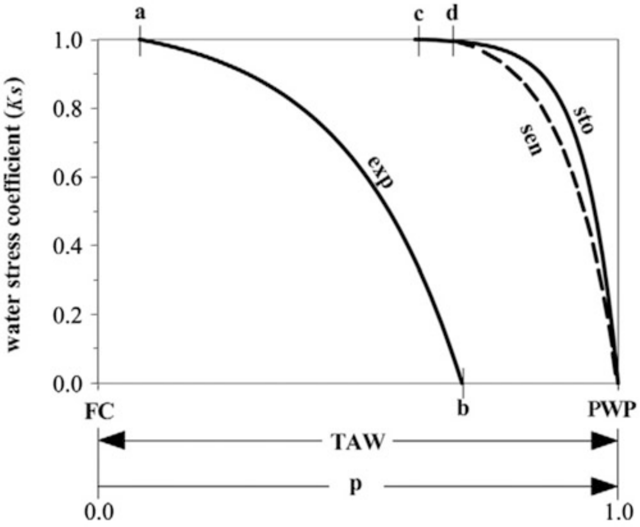


Fig. 11.12 Relationship between stress coefficients (Ks) for leaf expansion (exp), stomatal conductance (sto) and canopy senescence (sen) and relative availability of soil water. (Steduto et al. 2009)

$$\mathrm{CGC_{adj}} = \mathrm{Ks_{exp}} * \mathrm{CGC}$$

As $\mathrm{Ks_{exp}}$ ranges from 1 to 0, the rate of canopy growth starts to decline from its potential rate when depletion of soil water reaches the upper threshold and stops completely when the depletion reaches the lower threshold. AquaCrop permits growth of canopy cover up to 50% flowering, especially in determinant crops, water stress during this period prevents the canopy cover to reach its maximum resulting in smaller canopy size. If water stress becomes severe, it can also trigger the canopy senescence during its development phase.

Senescence of the canopy can be accelerated by severe water stress any time during the life cycle. This is estimated by adjusting canopy death coefficient (CDC) through the water stress coefficient for the acceleration of senescence ($\mathrm{Ks}_{\mathrm{sen}}$), with the following equation:

$$\mathrm{CDC}_{\mathrm{adj}} = (1 - \mathrm{Ks}_{\mathrm{sen}}) * \mathrm{CGC}$$

InfoCrop In the initial stage of development (when LAI is less than 0.75), leaf growth rate is mainly influenced by temperature and moderated by nitrogen stress and not by water stress. Thereafter, growth rate in LAI (RLAI) is calculated based on initial LAI (LAII), leaf area growth rate (GLAI), death rate of LAI (DLAI) and net loss of LAI due to pests (LALOSS) and transplanting (Aggarwal et al. 2004).

$$\mathrm{RLAI} = \mathrm{LAII} + \mathrm{GLAI} - \mathrm{DLAI} - \mathrm{LAI} * (1 - \mathrm{PLTR}) - \mathrm{LALOSS}$$

Simulation of senescence (DLAI) is based on several empirical constants relating to shading, ageing, nitrogen mobilization, temperature, water stress and death due to pests and diseases. The water stress accelerates senescence depending upon its severity.

CropSyst The increase of leaf area during the vegetative period, expressed as leaf area per unit soil area (leaf area index, LAI), is calculated as a function of biomass accumulation, specific leaf area and a partitioning coefficient. Leaf area duration, specified in terms of thermal time and modulated by water stress, determines canopy senescence (Stockle et al. 2003).

STICS Leaf growth in STICS is simulated in various ways. The standard option has the net balance of growth and senescence. The option of simulating effect of stresses (water and nitrogen) on senescence is also available in STICS. The concept of lifetime (in degree days) is applied to above-ground biomass production, taking into account the senescence induced by water stress and nitrogen stress. The effect of severe water, nitrogen and low temperature stresses on leaf area is simulated through setting a threshold (0.7 for the minimum of water stress and nitrogen stress indices) which causes reduction in accumulation of biomass induced by senescence. It is also assumed that this loss in biomass cannot be compensated by the growth of new leaves (Brisson et al. 2003).

Effect of water stress on leaf growth is expressed as

$$\begin{aligned}\mathrm{ll\,DELTAI} = {} & \left(\frac{\mathrm{DLAIMAX}}{[1 + \mathrm{emp}\ 5.5(2.2 - \mathrm{ULAI})]}\right) * (\mathrm{TCULT} - \mathrm{TCMIN}) \\ & * \min(\mathrm{TURFAC}, \mathrm{INNS})\ \mathrm{EFDENSITE} * \mathrm{DENSITE}\end{aligned}$$

where DELTAI is the net leaf growth, DLAIMAX is the maximum rate of setting up of LAI, ULAI is the physiological time unit for calculation of LAI between day of seedling emergence and the first day of maximum LAI, TCULT is the canopy temperature (assumed to be the average of maximum canopy temperature and minimum canopy temperature), TCMIN is the minimum temperature of growth, INNS is the nitrogen stress factor, EFDENSITE is the planting density effect and DENSITE is the plant density.

WOFOST Leaf growth is driven by the increase in leaf biomass, and its conversion to leaf area is done by specific leaf area (m^2/g of dry biomass). Thus, water stress does not affect leaf growth directly, rather affected via effect on leaf biomass. However, leaf senescence may be induced by drought stress (Boogaard et al. 2014).

11.7 Effect of Water Stress on Dry Matter Production

DSSAT CERES model uses the radiation efficiency approach to calculate daily plant growth rate. In this model, potential growth rate is modified by the stresses like temperature; water deficit and surplus; nutrient deficiency, mainly nitrogen; and soil fertility. The daily plant growth rate (per plant basis) is calculated as

$$\mathrm{PCARB} = \frac{\mathrm{RUE}*\mathrm{PAR}}{\mathrm{PLTPOP}}\left(1 - e^{(-\mathrm{k}*\mathrm{LAI})}\right)*\mathrm{CO}_2$$

where PCARB = potential growth rate (g/plant), RUE = radiation use efficiency (g/MJ), PAR = photosynthetically active radiation (MJ/m^2/day), PLTPOP = plant population (plants/m^2), k = light extinction factor, LAI = leaf area index and $CO_2 = CO_2$ modification factor.

PCARB is modified by the stresses (varies from 0 to 1) and follows the law of limiting factor. It means PCARB is modified by the most limiting stress among all accounted stresses. The actual growth rate (CARBO) is calculated as

$$\begin{aligned}\mathrm{CARBO} = {} & \mathrm{PCARB} * \mathrm{AMIN1}(\mathrm{PRFT}, \mathrm{SWFAC}, \mathrm{NSTRES}, (1.0 - \mathrm{SATFAC})) \\ & * \mathrm{PGFAC3}\end{aligned}$$

where PRFT = temperature effect, SWFAC = water deficit effect, NSTRES = nitrogen stress effect, SATFAC = water surplus (waterlogging) effect and PGFAC3 = soil fertility factor effect.

APSIM: Generic Plant Module Effect of soil water stress on biomass accumulation ($f_{w,photo}$) is accounted as follows (Source: https://www.apsim.info/Documentation/Model,CropandSoil/CropModuleDocumentation/Plant.aspx):

$$f_{w.photo} = \frac{W_u}{W_d}$$

where 'W_u' is the total daily water uptake from root system and 'W_d' is the soil water demand of leaf and reproductive parts.

Water-limited biomass production (ΔQ_w) is restricted by water uptake when 'W_u' is less than 'W_d' (i.e. $f_{w.photo} < 1$).

AquaCrop AquaCrop model computes the daily above-ground biomass (B) by multiplying the normalized water productivity (WP*) with ratio of daily transpiration (Tr) to daily evaporative demand of the atmosphere (ETo) and expressed as follows:

$$B = WP^* \left\{ \frac{Tr}{ETo} \right\}$$

Thus, water stress affects the biomass production in AquaCrop by influencing the transpiration. The reduction in transpiration due to water shortage is simulated by multiplying transpiration under well-watered condition (Tr_x) with water stress coefficient for stomatal closure (Ks_{sto}).

$$Tr = Ks_{sto} * Tr_X$$

InfoCrop InfoCrop utilizes the radiation use efficiency (RUE)-based approach for dry matter production. The RUE of plant is affected by abiotic (temperature, CO_2, nitrogen stress and water stress) and biotic factors. Water stress reduces RUE almost in proportion to severity.

CropSyst CropSyst calculates the daily potential biomass production using two approaches, i.e. based on crop potential transpiration (B_{PT}) and on crop-intercepted PAR (B_{IPAR}). The potential biomass production for the day (B_P) is taken as the minimum of B_{PT} and B_{IPAR}. This potential growth is then corrected by water and nitrogen limitations, if any. The transpiration-limited biomass production (B_T) is calculated by multiplying B_{PT} with water stress index, i.e. ratio of actual transpiration to potential transpiration.

STICS STICS utilizes the RUE approach to calculate daily dry matter production. Species and phenology-dependent maximal RUE is reduced by abiotic stresses, i.e. temperature, CO_2, water and nitrogen stresses.

Effect of water stress on above-ground biomass is represented as

$$\begin{aligned} DLTAMS * 100 = {} & \left[EBMAX * RAINT - 0.0815 * RAINT^2 \right] * f(TCULT) \\ & * SWFAC * INNS \end{aligned}$$

where DLTAMS is the daily growth rate, EBMAX is the maximum radiation use efficiency, RAINT is the solar radiation intercepted by the crop, TCULT is explained before, SWFAC is the water stress factor and INNS is the nitrogen stress factor.

WOFOST WOFOST calculates dry matter production as a function of gross canopy photosynthesis, depending upon the detailed calculations of the distribution of light within the canopies. Crop responds to water stress with closure of stomata, as a consequence, CO_2 supply diminishes, and photosynthesis is reduced. This is quantified through product of water stress factor [ratio of actual transpiration rate (Ta) to potential transpiration (Tp)] and potential assimilation rate (Ap).

$$A = \frac{Ta}{Tp} * Ap$$

where A is the actual assimilation rate.

11.8 Effect of Water Stress on Dry Matter Partitioning

DSSAT In both CERES and CROPGRO module of DSSAT, allocation of photosynthates into different organs, viz. leaf, stem, root and storage organ, at different growth stages depend upon the assimilate availability. Above-ground biomass has priority for assimilates; the remaining assimilates at the end of day are diverted to roots. Until reproductive stage, all assimilate goes to vegetative tissues; thereafter, storage organ progressively receives the priority. But under water stress condition, the partitioning of photosynthates or assimilates shifts towards roots (Anapalli et al. 2008). In CROPGRO module, partitioning of assimilates during vegetative stage is governed by the following formula:

$$Xi * E(Pg - Rm)$$

where Xi represents partitioning factors for leaves, stem and roots, E is the conversion efficiency for photosynthates, Pg is gross photosynthesis rate (g CH_2O Day^{-1} m^{-2}) and Rm is the maintenance respiration rate.

The following expression in CROPGRO model adjusts biomass allocation to root under water stress:

$$FRRT = FRRT + ATOP * \left(1.0 - \left(AMIN\left(SWDF1, NSTRES\right) * (1.0 - FRRT)\right)\right)$$

where FRRT is fraction of photosynthate that goes to roots on a day and ATOP is maximum fraction change in biomass allocation from shoot to root; if water or nitrogen stresses occur, NSTRES is nitrogen stress factor. As TURFAC drops below 1.0, a certain fraction (ATOP) of assimilate normally partitioned to leaves and stems is diverted to roots.

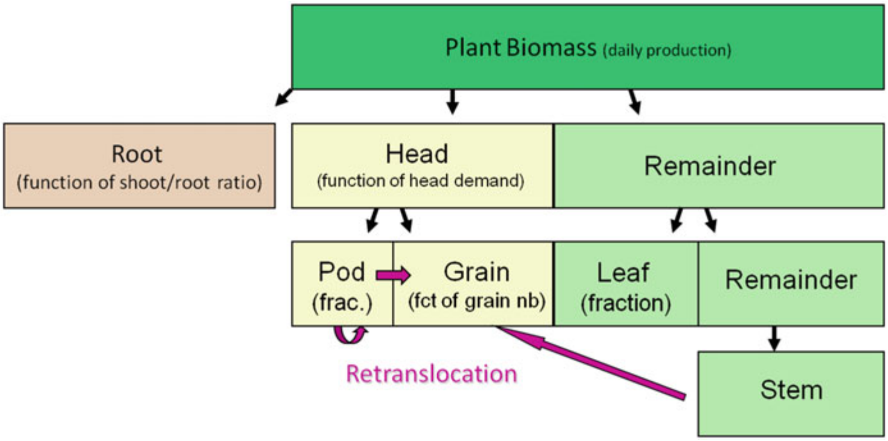


Fig. 11.13 Rules followed for biomass partition in the APSIM-Wheat module. Texts in the parentheses are partitioning methods for different plant parts. (Source: https://www.apsim.info/Documentation/Model,CropandSoil/CropModuleDocumentation/Plant.aspx)

During reproductive stage, kernel number per plant and kernel growth are also influenced by water stress in CERES model. But in CROPGRO module water stress does not affect grain growth directly, it affects via photosynthesis.

APSIM: Generic Plant Module In APSIM, allocation of dry matter to root is based on the root to shoot ratio. The above-ground biomass is then partitioned to head part depending upon the demand from pod and grain. The fraction of remaining dry matter is first allocated to the leaf and then to the stem. Re-translocation of assimilates from stem to head part may occur during grain filling, if sufficient assimilate is not available (Fig. 11.13). Water stress does not influence the partitioning of dry matter directly; it is affected through influence on photosynthesis.

AquaCrop The AquaCrop does not simulate the partitioning of biomass into different organs like root, stem, leaf, etc. It does the partitioning of biomass (B) into yield (Y) only by means of actual harvest index.

$$Y = f_{HI} * HI_O * B$$

'HI_o' is the reference harvest index under nonlimiting condition, which is modulated by stress factor (f_{HI}). The effect of magnitude and period of water or temperature stress on harvest index is simulated through a factor 'f_{HI}' in AquaCrop. Generally water stress has inhibitory effect on HI, but it can have reverse effect on HI, by restricting vegetative growth, thus ensuring higher allocation of assimilates to grain or fruits. Thus the value of f_{HI} can vary between a crop-specific maximum (up to 1.6) and zero (complete failure) (Vanuytrecht et al. 2014). In the event of mild water stress during grain formation, which reduces canopy expansion, but not enough to cause closure of stomata and retard photosynthesis, f_{HI} is modelled to rise above 1. So f_{HI} is a function of stress coefficient of expansion (Ksexp) and stomatal closure (Kssto). There are different stress coefficients for temperature and water stresses, which affects the pollination which results in a 'f_{HI}' smaller than 1. As a consequence of reduction in grain filling period due to stress-induced early senescence, f_{HI} and HI will be reduced.

InfoCrop Based on developmental stage-dependent crop-specific functions, dry matter available for crop growth is partitioned into roots, leaves, stems and storage organ. Roots get the priority for allocation, and it gets increased allocation of assimilates in case the crop experiences water or nitrogen stress. The remaining dry matter is allocated to above-ground shoot, from which a fraction is allocated to leaves and stems. The balanced dry matter is automatically allocated to the storage organ. The number of storage organ and grain filling rate is not directly influenced by water stress, as it influences the effect of water stress on dry matter production.

CropSyst CropSyst simulates the partitioning of dry matter to yield component only, which is based on harvest index. The harvest index is determined using the unstressed harvest index as base, a required crop input parameter, modified according to crop stress (water and nitrogen) intensity and sensitivity during flowering and grain filling.

STICS STICS simulates the total biomass of the plant and separately accounts for structural biomass of stem, green leaves and dead leaves and the reserves of the plant, which are not localized between organs (Strullu et al. 2014). The total biomass of leaves consist of biomass of green leaves and yellow leaves. Biomass of green leaves depends upon the LAI and maximum specific leaf area index (SLAMAX). The difference between actual specific leaf area and SLAMAX corresponds to remobilized leaf carbon. Biomass of yellow leaves is calculated in the senescence module. Water stress affects the portioning of dry matter to leaves by affecting LAI and senescence processes. Partitioning of biomass to structural component of stem is calculated as a constant proportion of total mass of leaves, i.e. green leaves plus yellow leaves. The harvested organ calculation depends upon the grain to shoot biomass ratio as a function of development stage. The reserve components are calculated as the difference between the total biomass and accumulated biomass of leaves, stem and harvested organ.

WOFOST WOFOST simulates the developmental stage-dependent dry matter partitioning through partition tables. The fraction of assimilates is allocated to the root first; the remaining fraction is distributed to above-ground portion, i.e. leaves, stems and storage organs. Water stress affect the partitioning of dry matter by affecting the availability of assimilates.

11.9 Intercomparison of System Model Output: Case Studies for Water Stress Management

Todorovic et al. (2009) compared the performance of AquaCrop, WOFOST and CropSyst models for simulating growth of sunflower under different water regimes in Mediterranean environment. The reason for choosing these three models is that they differ in the level of complexity describing crop development, in the main growth modules driving the biomass simulation and in the number of input parameters. The mechanism of simulation of biomass in AquaCrop is exclusively water driven, while CropSyst is based on both water- and radiation-driven modules, and WOFOST uses the carbon-driven approach for dry matter production. They found that estimation of phenological stages was almost similar for all models because of utilization of same heat unit concept. In the course of development, CropSyst over-predicted LAI development, whereas WOFOST provided convincing results before anthesis. Maximum LAI at anthesis is also over-predicted by CropSyst, whereas WOFOST under-predicted LAI by 2%. However, senescence followed the measured LAI trend in all models. All the models underestimated the yield under severe water stress conditions. Simulation of biomass growth by WOFOST was better than other two models under rainfed and deficit irrigation, because the latter involves simpler physiological sub-models accounting for the impact of water stress on biomass growth and its partitioning to yield. Simulation of water use efficiency (WUE) was better with CropSyst than other models under limited water supply.

Rotter et al. (2012) evaluated the performance of nine system models (APESACE, CROPSYST, DAISY, DSSAT-CERES, FASSET, HERMES, MONICA, STICS and WOFOST) for simulating growth of spring barley (*Hordeum vulgare* L.) at seven sites in Northern and Central Europe. They reported that models which are predicting well the phenology were not necessarily better predictors of grain yields. Among the studied models, the grain yield is better estimated by HERMES, MONICA, WOFOST and DAISY than others.

Battisti et al. (2017) studied the performance of five soybean models (FAO – agroecological zone, AquaCrop, DSSAT CSM-CROPGRO-soybean, APSIM Soybean and MONICA) under both rainfed and irrigated conditions in southern Brazil. DSSAT and APSIM were found to be better estimators of phenology, because they accounted for the effect of water stress and nitrogen limitation on crop development rate besides thermal time and photoperiod. Under rainfed condition, APSIM and DSSAT simulated more drastic reduction in LAI due to water deficit during middle to end of crop cycle, while MONICA was found less effective for the same.

Akinseye et al. (2017) compared the performance of DSSAT, APSIM and SAMARA crop models for West African sorghum cultivars. APSIM and SAMARA could simulate phenology (anthesis and physiological maturity) with the lowest value of RMSE (<7 days) compared to DSSAT, for all the studied cultivars, except cv. IS15401 (highly photosensitive). The error in prediction of grain yield and biomass was comparatively higher during calibration and validation. The highest error was observed in SAMARA, followed by DSSAT and least for APSIM. Being more mechanistic APSIM and SAMARA crop models have a higher sensitivity of the adjustment of key parameters, especially specific leaf area for APSIM in low photoperiod-sensitive varieties, while SAMARA shows a higher response to changes in parameters for high photoperiod-sensitive varieties.

The capability of CSM-CROPGRO-peanut model to simulate growth and development of peanut was studied by Soler et al. (2013). Apart from simulating growth and development, they determined the relationship between yield and the two cumulative drought stress indices simulated by the peanut model at Griffin, USA. The cropping system model (CSM)-CROPGRO-peanut model was able to accurately simulate growth and development of peanut grown under different irrigation treatments as compared to the observed data. We found an inverse relationship between the two simulated total cumulative drought stress indices for leaf growth (expansion), photosynthesis and simulated pod yield.

Jin et al. (2016) assessed the heat and drought stress algorithm of 16 major models of maize by integrating into APSIM with its ensemble simulations. There was a wide variation in water shortage patterns simulated by different algorithms over the growing season. However, all the algorithm predicted the reduction in annual yield due to water stress. They found that sensitivity of reduction in yield to heat and drought stress was more in case of latter than that of former for the US Midwest since the1980s.

Eitzinger et al. (2004) compared the performance of CERES, WOFOST and SWAP models in simulating soil water content during growing season in Austria under different soils (chernozem, sandy chernozem and fluvisol) with a 2 m profile depth. In contrary to WOFOST, CERES and SWAP could simulate the grain yield of barley and wheat better. There was no distinct difference in simulating soil profile water content by all three models. The uncertainty in the simulation of soil water content varied with model and soil type; root mean square error (RMSE) of soil water content ranged from 0.71 to 4.67% for barley and 2.32 to 6.77% for wheat. It was also observed that all the three models overestimated soil water depletion pattern. Both CERES and SWAP models simulated the soil water content dynamics well in the surface soil (up to 30 cm). The study highlighted the superiority of multiple layer approach models like SWAP and CERES with more advanced estimation methods for root growth and soil water extraction over WOFOST.

WOFOST model failed to simulate the real field conditions, which may be attributed to the fact that it considers soil water content in the entire root zone is homogeneous. This assumption fails in soils with irregular drying and wetting cycles with various amounts of water as detailed by van den Berg et al. (2002).

O'Leary in 2000 had reviewed the performance of APSIM and DSSAT (CANEGRO) with sugarcane under water stress conditions for prediction of sucrose yield. He has discussed that APSIM-sugarcane failed to accurately simulate sucrose yield under significant water stress. It is also mentioned that the likely reason for this may be the fact that effect of water stress on sucrose partitioning are much more complex than the effect of stress accounted in APSIM-sugarcane (stalk partitioning, biomass accumulation and leaf area). Major difference between APSIM-sugarcane and CANEGRO in the method by which carbon is fixed into biomass is also pointed out.

11.10 Discussion on Approaches Used for Modelling Crop Growth Processes

Crop growth models differ in basic principles of crop growth process involved, parameterization and their sensitivity. Table 11.1 provides an overview of basic modelling approaches with emphasis on water stress effect on growth and development. All the crop models employ either capacity model (tipping bucket approach) or solution of Richard's equation to describe the water movement through soil. Among the seven models discussed in this chapter, only CropSyst has both the options, and all other six crop models followed capacity model approach. There were mainly two approaches used for quantifying water stress factor – defining a critical limit of soil moisture value and ratio of actual to potential transpiration (AT/PT). CropSyst and InfoCrop followed the AT/PT concept, and all other five crop models followed the former concept. The value of water stress factor ranged from zero to

Table 11.1 Comparison of different principles and characteristics of crop simulation models discussed in this chapter regarding soil water balance and water stress factor

Model[a]	WO	ST	AQ	CR	AP	DS	IN
Soil water movement[1]	C	C	C	C/R	C	C	C
Stresses involved[2]	W, N	W, N	W, N	W, N	W, N, P	W, N, P	W, N
Water stress factor[3]	Ct-SM	Ct-SM	Ct-SM	AT/PT	Ct-SM	Ct-SM	AT/PT
Crop phenology[4]	f (T, PP)	f (T, PP)	f (T)	f (T, PP, V)	f (T, PP, V)	CERES: f(T) CROPGRO: f(T, PP, V)	f(T, PP, V)
Dry matter production[5]	CD	RD	WD	WD & RD	RD	CERES: RD CROPGRO: CD	RD
Yield formation[6]	Y (Prt, Bm)	Y (HI (Gn), Bm)	Y (HI, Bm)	Y(HI, Bm)	Y(HI, Bm)	Y[HI (Gn), Bm]	Y(Prt)

[a] Model abbreviations: *WO* WOFOST, *ST* STICS, *AQ* AquaCrop, *CR* CROPSYST, *AP* APSIM, *IN* INFOCROP

[1] *C* capacity approach, *R* Richard's equation

[2] *W* water, *N* nitrogen, *P* phosphorus

[3] *Ct-SM* critical threshold of soil moisture, *AT/PT* ratio of actual to potential transpiration

[4] *T* temperature, *PP* photoperiod, *V* vernalization

[5] *CD* carbon driven, *RD* radiation driven, *WD* water driven

[6] *Prt* partitioning after anthesis, *Bm* above-ground biomass, *HI* fixed harvest index, *Gn* grain number

one in all the seven crop models, where zero represented maximum stress and one represented no stress, except CropSyst, where the converse was true.

All the models use the thermal time concept to simulate the phenological development, and other factors like photoperiod, vernalization factors, water stress, nitrogen stress, etc. act as modifier on it. Except DSSAT-CERES and AquaCrop, all studied models account the effect of water stress on phenology. Phenological development in DSSAT-CERES and AquaCrop is based on temperature only.

In all models, leaf expansion is considered to be most sensitive process for water deficit stress. The sensitivity of water stress for different physiological processes like leaf expansion, senescence, nitrogen fixation, photosynthesis, etc. is explained by linear interpolation between stress factors and soil water availability. However, this relationship in AquaCrop is convex in nature which is the result of adjustments by the crop to cope with the developing water stress that improve with time its resistance to stress (Steduto et al. 2009). Except AquaCrop, all models simulate the leaf area index. Canopy cover is a distinctive feature of AquaCrop because expansion, ageing, senescence, amount of transpiration and biomass are determined through it.

Simulation of dry matter production in most of crop models is based on three concepts, i.e. water driven, radiation driven and carbon driven (Steduto 2003). DSSAT-CERES, APSIM, InfoCrop and STICS models use the radiation-driven approach for dry matter production, while AquaCrop uses the water-driven approach. However, CropSyst model utilizes both water- and radiation-driven approaches for calculating daily dry matter production. WOFOST and DSSAT-CROPGRO are based on carbon-driven approach. Water stress reduces the dry matter production in all models by multiplying stress factor to it. AquaCrop and CropSyst simulate the partitioning of dry matter to only yield part through harvest index (HI), rather than to different organs like the root, stem and leaf. Water stress in these models affects the partitioning by influencing the harvest index. Except DSSAT, all models provide the priority for allocation of dry matter to root first, and then the remaining part is allocated to other organs. During water stress, partitioning of dry matter shifts towards the root.

Simulating drought stress timing and severity requires the accurate estimation of soil water holding capacity and daily plant water use. Errors in simulating leaf dry weight and leaf area accumulation will have magnifying effect through affecting dry matter production, and its partitioning resulted into inaccurate simulation of water stress impact on overall growth and development (Prasad et al. 2008). Previous studies have shown that crop models were not able to adequately simulate water use efficiency, particularly under water deficit stress conditions (Todorovic et al. 2009, Evett and Tolk 2009). Increasing water use efficiency of crops will be a top research priority across the globe at large and rainfed areas in particular. Application of crop models to address this issue will depend upon understanding the processes involved in a more detailed manner and representing the concepts effectively in the models.

11.11 Summary

The crop models were initially designed to see the impact of crop management and weather on yield. With the improvement in our understanding about complexity of processes involved, new-generation crop models with range of applications like impact of climate change on crop production, crop phenotyping for drought or temperature stress, etc. were developed. Still many processes are not quantified satisfactorily in crop models under stress environments like water, nutrients and extreme temperature, causing uncertainty in growth and yield simulations, and need to be improved (Antle et al. 2017). Among the abiotic stresses, water deficit is considered to be the most limiting factor. In present context, our chapter started with brief critical overview of effect of water deficit on plant physiological processes of growth and development. Subsequently, we have presented the approaches which describe the quantitative measure of water stress accounted by seven widely used crop models, viz. DSSAT, APSIM, AquaCrop, WOFOST, CropSyst, InfoCrop and STICS. Further, we attempted to provide information on how these crop models simulate the impact of water stress on phenological development, leaf expansion and canopy growth, dry matter production and its partitioning. The chapter was concluded with case studies on intercomparison of models evaluation under water deficit stress conditions.

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Hyperspectral Remote Sensing: Use in Detecting Abiotic Stresses in Agriculture

12

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Abstract

Abiotic stresses are one of the major factors affecting crop production in many parts of the globe. The need of the hour is to reduce the yield losses due to these abiotic stresses. In this connection, early detection and corrective measures can help to reduce the impact of stresses on crop growth and yield. The recent developments in remote sensing particularly hyperspectral remote sensing hold a major key in early detection of abiotic stress over a larger area with less involvement of cost, time and labour. The works relevant to abiotic stress characterization particularly water and nutrient stress based on plant spectral reflectance are dealt in this chapter. The research work done previously elucidates that the water and nutrient monitoring through remote sensing is possible. The remote sensing-based techniques can lead to the development of real-time management of water and nutrient stress, thereby reducing the yield losses due these stresses.

Keywords

Abiotic stress · Hyperspectral remote sensing · Water-deficit stress · Nutrient stress · Crops

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12.1 Introduction

Abiotic stresses are the major factors affecting crop yield in addition to biotic factors. The abiotic stressors like temperature (high/low), water (drought, flooding/hypoxia), radiation (UV, ionizing radiation), chemicals and salinity are responsible for the major reduction in agricultural production. According to world estimates on an average, 71% yield losses in agricultural crops are caused by abiotic factors (Boyer 1982). These comprise mostly of high temperature (40%), salinity (20%), drought (17%), low temperature (15%) and other forms of stresses (Ashraf et al. 2008). Biotic stress, on the other hand, is caused by living organisms, such as bacteria, viruses, fungi, insects, herbivores and other plants; competition is an additional challenge inducing a strong pressure on plants (Strauss and Zangerl 2002; Maron and Crone 2006. The other plants/weed competition causes the highest potential yield loss to the tune of 34% (Oerke 2006). Loss due to diseases range from 20% to 30%; in case of severe infection, the total crop may be lost, whereas estimated global loss due to insect pests is 18% (Oerke 2006). The impact of stresses imposed on a plant depends on climate, host plant and its resistance to particular stresses. The effect of biotic and abiotic stress on crop growth is usually detected only after it becomes visually apparent. Sometimes the detection can be too late to avoid crop yield loss. So, monitoring agricultural crop conditions throughout the growing season will help in accurate and timely assessment of yield loss caused by biotic and abiotic stresses which are very critical for countries where the economy is dependent on the agriculture. Early assessment of yield reductions will also help in strategic planning and avoiding disastrous situation (Doraiswamy et al. 2003). Field-scale assessment of continuous crop condition is time-consuming, laborious and location specific. Remote sensing, on the other hand, may provide an effective substitute to field sampling for crop condition monitoring. Moreover, it can give continuous coverage of a large area (Sepulcre-Cantó et al. 2006; Ullah et al. 2012). Non-destructiveness is another advantage of remote sensing techniques (Sepulcre-Cantó et al. 2006; Ullah et al. 2012). However, previous findings have revealed that considerable limitations exist when using images taken by multispectral satellite sensor to detect biotic and abiotic stresses (Hunt Jr and Rock 1989), whereas airborne or ground spectrometers having greater spatial, as well as spectral, resolution were able to detect spectral changes corresponding to changes in crop condition with more accuracy (Goetz et al. 1985). Arial hyperspectral sensors and field spectrometers have the ability to capture the electromagnetic spectrum at very narrow contiguous wavebands. This feature permits the remote detection and characterization of crop conditions from canopy reflectance as the latter change with the former (Peñuelas et al. 1997; Ustin et al. 1998; Stimson et al. 2005).

12.2 Remote Sensing for Detection of Stresses

Remote sensing is a science-art and technology for gathering information about an object without coming into physical contact with it (Jensen 2009). Thus it is a useful technique for visualizing, diagnosing and quantifying vegetation stress. Vegetation stress can be detected using three types of remote sensing which are as follows:

1. Thermography
2. Fluorescence
3. Reflectance

Thermography or thermal remote sensing is utilized to study water-deficit stress (Guilioni et al. 2008), while fluorescence imaging is used to monitor photosynthetic efficiency of the plant (Chaerle et al. 2002). Fluorescence emission from a healthy leaf when excited by UV-A radiation consists of blue (440 nm), green (520 nm), red (690 nm) and far-red (740 nm) wavelengths. In reflectance-based remote sensing, the electromagnetic signal reflected off the plant leaves is the recorded data. The parameter monitored in reflectance-based remote sensing for plant stress is change in leaf constituents.

12.3 Effect of Stress on Plant's Spectral Signature

The prime objective of remote sensing is to separately recognize an object or feature from its surroundings. This can only be done by knowing the characteristic spectral properties of the object which are popularly known as signatures. If this is achieved through the reflectance measurements, then it is called as spectral reflectance. The spectral reflectance of the vegetation varies with the wavelength, and it can be divided into three main broad regions in the wavelength region 400–2700 nm (Gates et al. 1965).

1. In the visible spectrum (400–700 nm), the pigmentation of leaf, namely, chlorophyll, carotene and xanthophylls, dominates the response. This region is characterized by low reflectance and high absorbance, especially at blue and red wavelengths.
2. The response in the near-infrared (NIR) spectrum (700–1300 nm) is determined by the internal structure of the leaf. The discontinuity in the refractive index between the airspace and spongy mesophyll of the cell causes total internal reflection of the incident solar radiation resulting in very high reflectance

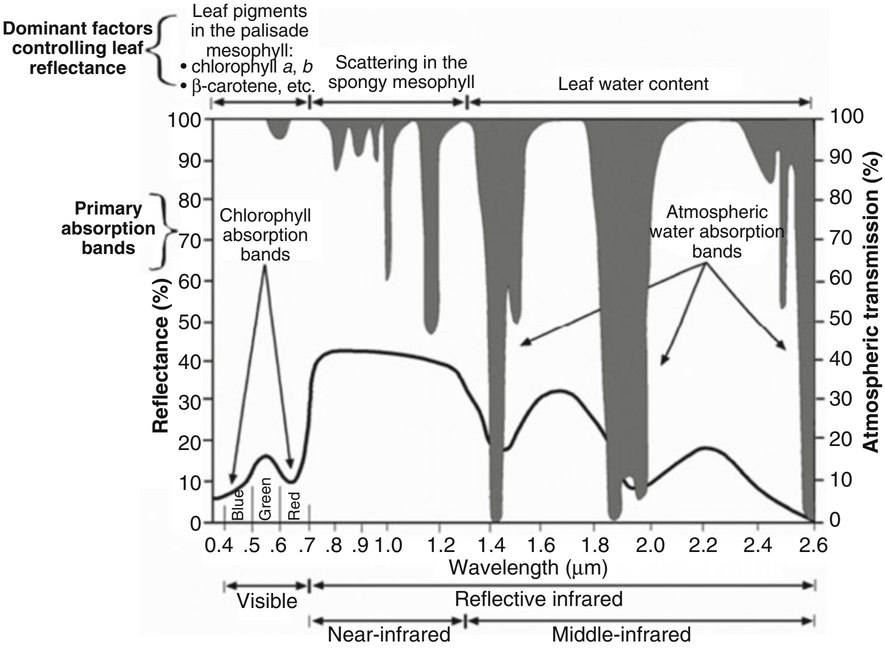

Fig. 12.1 Typical spectral reflectance pattern of leaf. Source: Jensen (2009)

(Gausman 1974). The NIR region has two weak water absorption features at wavelengths 950–970 and 1150–1260, respectively (Sims and Gamon 2002).

3. The response in the shortwave infrared (SWIR) spectrum (1300–2700 nm) is influenced to some extent by the internal structure of the leaves but is mostly influenced by the water content of the same due to the presence of the three major water absorption bands at 1400 nm, 1900 nm and 2700 nm in this region and other leaf biochemicals. Retrieving leaf water content based on remotely sensed data has been widely studied in the visible-near-infrared (VNIR) and SWIR spectra (Ceccato et al. 2002; Cheng et al. 2011). Water molecules present in leaves weakly absorb radiation in the NIR (720–1000 nm) region and strongly absorb in the SWIR (1400–1900 nm) region (Datt 1999). So, SWIR region is more sensitive and efficient in measuring leaf water content than NIR region (Datt 1999). Many studies reported strong correlation of leaf water content with reflectance and derivative spectra at wavelengths between 1400 and 1900 nm (Ceccato et al. 2001, 2002; Champagne et al. 2003). Due to biotic and abiotic stresses if the chlorophyll content is reduced, the reflectance in the visible region is increased. If disease or pest damages the leaves, the reflectance in the NIR region of the electromagnetic spectrum will be low. The typical spectral reflectance pattern of leaf is depicted in Fig. 12.1.

12.4 Abiotic Stress Monitoring

12.4.1 Water-Deficit Stress Monitoring

Water resources have faced continued pressure to meet the increasing demand of mankind (McGwire et al. 2000). This everlasting situation begs for more judicious use of irrigation water to avoid environmental problems like groundwater pollution, runoff, etc. along with minimizing expenses in affording such an invaluable input. Thus, ways to achieve this goal must be searched for. A promising approach could be timely application of just adequate amount of water so as to avoid crop stress as well as putting less pressure on water resources. In this regard, appropriate assessment of water-deficit stress is very much important. For this, several ways with varying extent of accuracy and applicability have been tried so far, for instance, measuring the water content of soil or plant, contents of pigments or nitrogen, dry matter and leaf area index (LAI) (Carter 1993; Peñuelas et al. 1994) which may act as bioindicators of water-deficit stress (Zarco-Tejada et al. 2004). Till date, most workers have used soil moisture sensors to detect water-deficit stress of crop plants. Though these sensors can fairly assess the imposed water-deficit stress, they fail to represent in most cases the level of water-deficit stress originally experienced by the plants (Sinclair and Ludlow 1985). Moreover such measurements are time-consuming and not that easy to employ at field level limiting their scale applicability. Contrarily, assessing the leaf water content may provide a better picture of plant's physiological response under differing extent of soil moisture scarcity and consequent water-deficit stress actually experienced by plants. Leaf water content can effectively indicate health and vigour of a plant along with its photosynthetic efficiency (Harry 2006). Apart from these, precise estimates of plant water content as a whole can be used for drought risk assessment (Bauer et al. 1986), selection of suitable genotypes in breeding for water-deficit stress tolerance (Munjal and Dhanda 2005), providing advanced prediction of wildfire and monitoring the physiological status of any vegetation (Peñuelas and Filella 1998) or biomass (Mutanga et al. 2005; Cho et al. 2007; Ullah et al. 2012). In agriculture, it can help in irrigation scheduling and crop yields estimation (Peñuelas et al. 1993, 1997).

Plant water-deficit stress or drought stress is one of the major limiting factors affecting yield and is usually detected only after it becomes visually apparent. So an accurate estimation of plant water status or relative water content (RWC) is a major factor in the decision-making process regarding general land use, crop irrigation and drought assessment (Peñuelas et al. 1997). RWC can be defined as the ratio of volume of water present in a leaf to the water volume of leaf at fully turgid condition (Hunt and Rock 1989). Assessment of water-deficit stress can be done by taking plant canopy or leaf level reflectance measurements, as they show change in response with changing RWC of the plant (Gutierrez et al. 2010). Different species may exhibit different symptoms of water-deficit stress; however, one of the common effects of water-deficit stress across all the species is the change in plant's spectral response changes with increase in moisture deficit (Peñuelas et al. 1993). The water absorption bands can be of good use in the estimation of the plant's RWC. Reflectance of plant leaf or canopy particularly beyond visible spectral range is mostly governed by leaf water content. Therefore, it can indirectly be used for non-destructive in situ evaluation of plant water status. Canopy reflectance obtained from hyperspectral sensors besides offering quick and easy measurements also enables estimation of some additional parameters through a series of different spectral indices (e.g. chlorophyll content, LAI, intercepted radiation and photosynthetic capacity) (Araus et al. 2001). For its versatile nature, canopy reflectance is a very useful tool for high-throughput phenotyping (Montes et al. 2007; Chapman 2008).

12.4.1.1 Spectral Indices for Characterizing Stress

The vegetation indices (VIs) are combinations of spectral responses in different wavebands which emphasize a particular feature of the vegetation. The indices are ideally a sum, difference, ratio or other linear combination of reflectance factors or radiance observation from two or more wavelengths/wavelength intervals (Wiegand et al. 1991). These composite indices are more sensitive than individual spectral bands for the detection of plants biophysical and biochemical properties as affected by biotic and abiotic stresses (Asrar et al. 1984). The indices also try to standardize the representation of the crop spectral responses which helps in region-to-region and year-to-year comparison and reduce the dimensionality of the multispectral/hyperspectral data (Malingreau 1989). Minimizing the variability in reflectance caused by illumination condition, instrument noise, atmospheric condition and soil background is the sole of using VIs (van Leeuwen and Huete 1996).

The water index (WI, R_{970}/R_{900}) introduced by Peñuelas et al. (1993) has been widely used to assess water status in different crops (El-Shikha et al. 2007). Based on WI, Babar et al. (2006) suggested two normalized water indices, viz. NWI-1 $= [R_{970} - R_{900}]/[R_{970} + R_{900}]$ and NWI-2 $= [R_{970} - R_{850}]/[R_{970} + R_{850}]$, to screen grain yield of spring wheat genotypes under well-irrigated and water-deficit conditions. Under rainfed conditions, two additional normalized water indices with slightly different wavelengths (NWI-3 $= [R_{970} - R_{880}]/[R_{970} + R_{880}]$ and NWI-4 $= [R_{970} - R_{920}]/[R_{970} + R_{920}]$) were used for screening the grain yield of advanced winter wheat lines (Prasad et al. 2007). These five water indices (WI and four NWIs) could explain a huge portion of variability in grain yield and could be used as alternative approach for selecting high-yielding wheat varieties for different environments (Babar et al. 2006; Prasad et al. 2007). The underlying hypothesis of WI is that the NIR wavelengths (970 nm) have deeper penetrability into the canopy, thus giving accurate estimates of water content (Babar et al. 2006; Prasad et al. 2007; Gutierrez et al. 2010). Stimson et al. (2005) found significant correlation ($r^2 = 0.44{-}0.71$) of leaf water content and water potential with normalized difference water index (NDWI; $[R_{860} - R_{1240}]/[R_{860} + R_{1240}]$) and normalized difference vegetation index (NDVI; $[R_{900} - R_{680}]/[R_{900} + R_{680}]$) in two conifer species (*Pinus edulis* and *Juniperus monosperma*).

The NDWI was developed for assessing water status from the airborne hyperspectral imagery having comparatively higher spatial resolution (Gao 1996). Being less sensitive to atmospheric scattering due to water vapours, NDWI is a fairly good indicator for vegetation water content. It can also function using the 1640 nm ($NDWI_{1640}$; $[NIR_{858} - SWIR_{1640}]/[NIR_{858} + SWIR_{1640}]$) and 2130 nm ($NDWI_{2130}$; $[NIR_{858} - SWIR_{2130}]/[NIR_{858} + SWIR_{2130}]$) water absorption bands (Chen et al. 2005). The Moisture Stress Index (MSI; R_{1600}/R_{820}) developed from ratio of Landsat Thematic Mapper band 5 to band 4 has also been found sensitive to changes in leaf water status (Hunt and Rock 1989). The correlation between MSI and the RWC of the tree species, such as *Picea* spp., *A. deserti*, *Q. agrifolia*, *L. styraciflua* and *G. max*, was found to be linear. Simple ratio water index (SRWI; R_{860}/R_{1240}) was found to be suitable for estimating plant water content relative to LAI, equivalent water thickness (EWT) and leaf biomass (Zarco-Tejada et al. 2003). The other spectral-based water indices which have been developed are normalized difference infrared index (NDII; $[R_{820} - R_{1600}]/[R_{820} + R_{1600}]$) (Hardisky et al. 1983), normalized multiband drought index (NMDI; $[R_{860} - (R_{1640} - R_{2130})]/R_{860} + (R_{1640} + R_{2130})]$) (Wang and Qu 2007), etc.

Application of narrowband VIs in estimating vegetation parameters has also been a success (Mutanga and Skidmore 2004; Darvishzadeh et al. 2008). The VIs (i.e. simple ratio, normalized difference indices) are based upon the difference in the reflectance spectra of two spectral bands (Rouse et al. 1974). To detect changes in plant water content, spectral indices, such as WI or NDWI, utilize simple ratios of the reflectance at a wavelength located within the water absorption bands, and another wavelength from outside the water absorption bands ideally used as a control (Sims and Gamon 2002). With declining plant water content, the decrease in energy absorption by water is more distinct for wavelengths inside the water absorption band leading to a change in the reflectance ratio. Indices like the normalized differential vegetation index (NDVI) and the red edge inflexion point (REIP) utilize wavelengths that are affected by changes in the cellular structure and/or pigment content of leaves (Horler et al. 1983). Unlike NDWI and WI, these indices account for spectral variances resulting from changes in leaf physiological properties which might be the indirect effect of changes in plant water content.

Most of the presently used indices, such as NDWI and WI, utilize wavelengths falling in the near-infrared (NIR, 700–1300 nm) region. Though multiple studies have shown the existent of significant relationships between these indices and plant water status (Peñuelas et al. 1997; Serrano et al. 2002; Pu et al. 2003; Asner and Martin 2008), many have criticized them based on the relative insensitivity of the employed wavelengths to changes in plant water content (Ceccato et al. 2002). It has been argued that wavelengths in the SWIR could better represent variations in plant water status than those in NIR (Tucker 1980). The SWIR wavebands located in the range of 1500–1750 nm have been identified as useful for monitoring plant water content (Ceccato et al. 2002; Chen et al. 2005; Eitel et al. 2006), fuel moisture content (Chuvieco et al. 2002) and other plant biochemical parameters (e.g. lignin and nitrogen) (Serrano et al. 2002).

12.4.1.2 Multivariate Modelling for Characterization of Plant Stress

However, the spectral indices mentioned above only make use of a limited number of bands. More information on crop water status may be extracted by investigating the entire spectrum. But the use of the entire spectrum of hyperspectral data has an associated problem of high degree of dimensionality and collinearity of the contiguous bands (Vaiphasa et al. 2005). Multiple linear regression (MLR) models developed from hyperspectral data generally suffer from multicollinearity and overfitting as in most of the cases, the number of predictors are equal or more than observations leading to a high R^2 (Curran 1989). Partial least square regression (PLSR), on the contrary, is the combination of principal component analysis (PCA) and MLR. It can effectively curb the problems of multicollinearity and overfitting (Cho et al. 2007). Thomas and Haaland (1990) reported PLSR as a robust technique for predicting leaf biochemical from hyperspectral datasets that simultaneously minimizes multicollinearity and model overfitting. PLSR simultaneously uses all spectral bands and selects uncorrelated variables from a set of explanatory variables (Geladi and Kowalski 1986), and by doing so it edges the problem of multicollinearity. For this reason, use of PLSR in remote sensing is continuously increasing (Li et al. 2005; Darvishzadeh et al. 2008; Asner and Martin 2008; Ramoelo et al. 2012; Li et al. 2014). Asner and Martin (2008) used PLSR analysis of leaf spectral and chemical data to determine strength of the relationship between foliar properties and canopy reflectance under diverse canopy structures. Johansson et al. (2003) introduced PLSR to formulate multivariate models for plant moisture content prediction. Ji et al. (2007) established quantitative estimation models for chlorophyll and water content in wheat leaves via PLSR. Some researchers have studied the feature selection in PLSR modelling. Darvishzadeh et al. (2008) reported that the retrieval accuracy of PLSR increased when some feature selection was applied to the data before running the PLSR while estimating LAI and leaf chlorophyll content from field spectral measurements. A number of leaf biochemicals have been successfully estimated by this technique (Huang et al. 2004; Asner and Martin 2008; Ramoelo et al. 2012; Das et al. 2018). Ullah et al. (2014) used the PLSR to estimate leaf water content from the reflectance spectra in VNIR-SWIR, MIR and TIR. Das et al. (2017) used MLR, multivariate adaptive regression spline (MARS), PLSR, random forest (RF) and support vector machine regression (SVR) model to estimate plant RWC. They reported PLSR as the best model for prediction of RWC ($R^2_c = 0.96$ and $R^2_v = 0.91$, respectively).

12.4.1.3 Characterization of Stresses through Plant Pigment Assessment

Leaf chlorophyll content decreases under stress condition, leading to a reduction in the overall absorption of light in the visible region (Zarco-Tejada et al. 2001). These changes affect the spectral reflectance signatures of plants through a reduction in green reflection and an increase in red and blue reflections resulting in changes in the normal spectral reflectance pattern of plant. When chlorophyll content is used as a measure of plant water-deficit stress, the placement and shape of the spectral red edge are important indicators of plant water status (Horler et al. 1983; Blackburn

2007). This relationship is used to explain the movement of the red edge to shorter wavelengths during expressions of plant water-deficit stress, such as senescence or stress-induced chlorosis which is known as blue shift (Carter 1993; Campbell et al. 2007). An approach like this can not only help in developing simple hand-held field instruments but also in studying the digital airborne or satellite images so as to assist the stakeholders in making informed decisions about crop management.

VIs have also been used to estimate chlorophyll content as affected by biotic and abiotic stresses. Datt (1999) proposed the $(R_{850} - R_{710})/(R_{850} - R_{680})$ index using leaf reflectance of 21 *Eucalyptus* species. Sims and Gamon (2002) developed some indices using a large database containing a wide range of functional types, leaf structure and development stage (nearly 400 leaves) and compared those with commonly used ones. They found that indices mSR705 and mND705 were much superior to others in respect of correlation with chlorophyll content. Broge and Leblanc (2001) made an evaluation among different indices developed from canopy scale simulated database. However, this model-based comparison did not have any relation to experimental spectra, and hardly any related study at leaf scale exists. Gitelson and Merzlyak (1994) observed that the highest sensitivity of reflectance corresponds to the highest absorption of light by chlorophyll-a at 670 nm. They inferred that 550–560 nm and 700–710 nm wavebands were most sensitive to chlorophyll-a content. For pigment estimation Blackburn (1999) identified the optimal individual wavebands, e.g. 680, 635 and 470 nm for chlorophyll-a, chlorophyll-b and carotenoids, respectively. Concentrations of both chlorophyll-a and chlorophyll-b in bracken (*Pteridium aquilinum*) were found to be best correlated with 676 nm (Blackburn 1998). In the same study, chlorophyll-a showed the highest correlation with 680 nm wavelength at senescence. Two indices, viz. R_{NIR}/R_{700} and R_{NIR}/R_{550}, have been formulated for chlorophyll assessment from the reflectance spectra of tobacco, maple and chestnut (Gitelson and Merzlyak 1994; Lichtenthaler et al. 1996; Gitelson et al. 1996). Gitelson and Merzlyak (1997) achieved error of less than 4.2 μg cm^{-2}, while predicting leaf chemicals through algorithm developed from the leaf optics validated over nine species in the chlorophyll content range of 0.27–62.9 μg cm^{-2}. Increase in canopy chlorophyll, either by leaf chlorophyll content or LAI, is expected to result in widening of major chlorophyll absorption at around 680 nm in reflectance spectra of any vegetation (Gitelson et al. 1996).

Steele et al. (2008) established a relation between chlorophyll content and the red edge chlorophyll index, described as CI_{red} edge = $[(R_{NIR}/R_{red}$ edge) $-1]$ in the red edge (710–720 nm) and NIR (755–765 nm) spectral regions. The CI_{red} edge, argued to be an accurate measure of grape leaf chlorophyll, is capable of predicting leaf chlorophyll in 3–515 mg m^{-2} range with a root mean square error (RMSE) of less than 28 mg m^{-2}. This relationship, validated using independent datasets including Edelweiss, Saint Croix and De Chaunac grape cultivars, was very accurate in chlorophyll prediction. Das et al. (2015) compared thirty VIs, namely, simple ratio, normalized and three-band indices for estimation of chlorophyll in wheat as affected by water-deficit stress. They have concluded that satisfactory prediction of chlorophyll can be obtained using VIs.

12.4.1.4 Thermal Hyperspectral Remote Sensing for Stress Characterization

Until recently vegetation spectra in the mid- and thermal-infrared region (MIR: 2.5–6.0 μm and TIR: 8.0–14.0 μm) have been considered as featureless. Most spectral features of plant leaves in the TIR domain have been overlooked due to lack of equipment, poor signal-to-noise ratio and the complex nature of the spectral characteristics of vegetation (Ribeiro da Luz and Crowley 2007). However, recent advances in TIR application lead to the discovery that the spectral signatures of fresh plants are dominated by epidermal materials of leaves (i.e. cell wall and cuticle; Salisbury 1986). The reflectance spectra of green leaves taken by high-resolution sensors in the TIR region revealed a broad range of distinctive spectral features (Salisbury 1986; Salisbury and Milton 1988). The spectral response of fresh and completely dried leaves measured in mid- to thermal-infrared region revealed significant variation in the mid-infrared spectral response, emphasizing the potential use of mid-infrared for leaf water content quantification (Gerber et al. 2011). Remotely sensed data using TIR radiation has been successfully used to detect water-deficit stress even before visual symptoms of the same appeared (Möller et al. 2006).

Fresh leaves showed the lowest MIR and TIR reflectance, and with decrease in leaf water content, reflectance increased. In the MIR, the variation in reflectance was more prominent between 2.5 and 3.0 μm (maximum reflectance of about 30%) and 3.5–5.8 μm (maximum reflectance of about 16%). The absorption characteristics at 3.05 μm and 4.65 μm are related to the leaf water content (Ribeiro da Luz 2006; Fabre et al. 2011). The water absorption feature at 4.65 μm became feebler with decreasing leaf water content, while the cellulose and lignin maxima at 4.00 μm and 5.52 μm became conspicuous (Fabre et al. 2011). Cheng et al. (2011) reported better retrieval of leaf water content retrieval from the MIR to TIR spectra ($R^2 = 0.88$) than that obtained from VNIR to SWIR spectra ($R^2 = 0.77$). The correlation between leaf water content and spectral response over the entire MIR region was reported to be negative (Ullah et al. 2013).

12.4.2 Nutrient Status Monitoring

One of the major challenges in front of the scientific community is to increase input use efficiency, and this compels us to implement competent techniques and farm technologies which are economically feasible and environmentally suitable. There are mainly two techniques namely soil and plant/leaf/tissue testing for rational fertilizer management. Among two approaches, the latter is more suited for monitoring the nutrient status and making decisions related to fertilizer nutrient application in standing crop. The traditional methods for leaf or tissue analysis need a thorough and comprehensive sampling, time and expensive laboratory biochemical analysis, which it practically not possible on a large scale, e.g. farmer's field. It is also very much applicable to tree crops, where crop nutrient status is truly reflected by leaf than the soil testing. The nutrient stress already disrupts the plant processes by the time the plant leaves express its deficiency symptoms, and the nutrient deficiency is diagnosed through the chemical analysis in the laboratory (Zhao et al. 2003).

Spectral features to determine biochemical nutrient concentration of different types of crops have been widely investigated and are becoming popular (Chen et al. 2011). The hyperspectral remote sensing data can be processed as in two ways, viz. narrow band or hyperspectral VIs and multivariate data analysis (Mulla 2013). Until recently research on remote sensing in agriculture was limited to developing red and NIR band-based VIs for nutrient stress monitoring (Hatfield et al. 2008). However, research has shown a remarkable improvement in retrieving information about crop through multivariate analysis of remotely sensed data over the traditional broadband VIs (Hansen and Schjoerring 2003; Nguyen and Lee 2006; Pimstein et al. 2007). N monitoring using remote sensing is a very well-developed area of research; however only a few attempts have been made in few crop plants on nutrients other than N (Samborski et al. 2009; Cohen et al. 2010; Herrmann et al. 2010).

Several indices (like NDVI) based on different diagnostic wavelengths have been developed for monitoring N in plants. The variation in spectral reflectance pattern of a wheat crop at different phenostages for different N stress levels has been studied (Ranjan et al. 2012). The findings revealed that the spectral reflectance pattern at the booting stage was most distinct for varying N stress level. A canopy reflectance-based ratio of data difference index (RDDI) was the best to predict the N in canopy of litchi at autumn shoot maturation stage, flower spike stage, fruit maturation stage and flowering stage with an accuracy of $R^2 > 0.5$ and $\text{RMSE}<0.14$. This implies the applicability of the canopy reflectance to estimate the litchi leaf N concentration, provided growth stage-specific models are used (Li et al. 2016). Under controlled environment, the macronutrient deficiency had exhibited effect on spectral reflectance pattern (Ponzoni et al. 1999; Araus et al. 2001). Latest research in this area demonstrated successfully monitoring of plant macronutrient using hyperspectral remote sensing (Chen et al. 2011; Pimstein et al. 2011; Knox et al. 2012; Zhang et al. 2013).

The concentration of P in plants is around 0.1–0.5%. Energy transfer and storage are the most important functions of P in plants. It is an essential component of adenosine di- and triphosphates (ADP and ATP). So, deficiency of P majorly disrupts energy-requiring processes, like membrane transport, photosynthesis, nucleic acid synthesis, biosynthesis of protein and phospholipids, etc. P deficiency-induced sugar accumulation enhances formation of a purple pigment anthocyanin in plants (Havlin et al. 2005). Osborne et al. (2002) developed stage- and time-specific MLR models of reflectance at selected wavelengths to predict P concentration in corn plants. At sixth leaf expansion growth stage (denoted as V6), linear model of 730 and 930 nm predicted P concentration in leaves significantly. Pimstein et al. (2011) used linear correlation analysis technique to identify P and K responsive wavelengths in wheat; they proposed the use of 1400–1500 nm and 1900–2100 nm as a potential region for developing P-based VIs. They found significant wheat canopy P prediction using proposed VI N_1645_1715 $((R_{1645} - R_{1715})/(R_{1645} - R_{1715}))$ in wheat canopy. One of the advantages of using these wavelengths is that they are located out of water absorption region and are usually included among the spectral bands of airborne hyperspectral images (Pimstein et al. 2011). Non-linear PLSR yielded the highest grass N and P estimation ($R^2 = 0.81$, RMSE = 0.08 and $R^2 = 0.81$, RMSE = 0.08, respectively) compared to conventional PLSR and remote sensing variables only (Ramoelo et al. 2013). Models having ancillary (geology, soil, fire, slope, aspect, altitude, etc.) and absorption variables had the highest N, P and fibre predictive capability ($R^2_{\text{adj}} = 0.49$–0.74) (Knox et al. 2012). Least square support vector machine (LS-SVM) model ($R_{\text{p}} = 0.88$) and PLSR model ($R_{\text{p}} = 0.75$) got the best prediction performance for determination of N, P and K content in grape leaves, respectively (Zhang et al. 2013). Pimstein et al. (2011) reported significant levels of accuracy of prediction in the retrieval of K and P in wheat plant using PLSR models.

Like P, concentration of S in plants ranges from 0.1% to 0.5%. S is an important component of S-containing amino acids – methionine, cystine and cysteine; these constitute about 90% of the total S in plants. Although S is not essential, it is a requisite for the chlorophyll synthesis. The deficiency symptoms of S appear first on younger leaves, which are many a time incorrectly diagnosed with N deficiency symptoms. S deficiency in plants leads to accumulation nonprotein N; this makes N: S ratio an important indicator of S status in plants (Havlin et al. 2005). The deficiency or sufficiency of P and S results differences in colouration and production of various chemical compounds which make their remote monitoring possible using remote sensing. One of the important functions of S is formation of disulphide bond (-S-S-) bond between polypeptide chains which determines structure and configuration of proteins. A characteristic absorption feature of disulphide bond is present in VIS region (500–600 nm). Pagani and Echeverría (2011) estimated S in upper and middle leaves of corn using leaf greenness under controlled S stressed condition. This is one of the earliest reports on S prediction using remote sensing in corn. They recorded significantly positive relationship between sulphur sufficiency index (SSI) and chlorophyll metre reading (CMR).

Ferwerda and Skidmore (2007) studied the ability of the hyperspectral remote sensing to predict the status of the nutrients (N, P, Ca, K, Na and Mg) in four wood plants: willow, mopane, olive and heather. In wheat crop, a proposed VI (P_1080_1460 = $(R_{1080} - R_{1460})/(R_{1080} + R_{1460})$) could predict the P status with significantly high accuracy ($r = 0.42$ and RMSE = 0.180 g m^{-2}). The proposed S VI (S_660_1080 = $(R_{1080} - R_{660})/(R_{1080} + R_{660})$) to retrieve S status had higher prediction accuracies than the traditional VIs (Mahajan et al. 2014). Similarly in rice, two VIs, i.e. NDVI hyper and NDVI broadbands, could predict canopy N with higher accuracy but failed to do so for P and S. The prediction accuracy of the VNIR- and SWIR-based VI NRI1510 ((R1510 − R660)/(R1510 + R660)) was the highest ($r = 0.81$, $p < 0.01$) for predicting canopy N status. New VIs were proposed based on the linear correlation analysis for remote detection of P and S. Proposed VI P_670_1260 ((R1260 − R670)/(R1260 + R670)) predicted the canopy P status with highest accuracy ($r = 0.67$, $p < 0.01$), whereas the highest prediction accuracy for canopy S ($r = 0.58$, $p < 0.01$) was recorded using the VI S_670_1090 ((R1090 – R670)/(R1090 + R670)) (Mahajan et al. 2016). They suggest that the proposed spectral algorithms could be used for real-time and site-specific N, P and S management in rice and wheat crop and for developing relatively low-cost hand-held sensors. Yanli et al. (2015) attempted to predict the N and P status of the citrus leaves using the hyperspectral remote sensing data. The results of their experiment revealed that Savitzky-Golay and PLSR methods were the best to predict N (Rp = 0.90, RMSEP = 0.1041) and P (Rp = 0.92, RMSEP = 0.0514). In a study by Galvez-Sola et al. (2015), NIR spectroscopy-based analysis and subsequent nutrient estimations for N, K, Ca, Mg, B, Fe, Cu, Mn, and Zn concentration were done using 217 leaf samples of different citrus trees species. The PLSR and different preprocessing treatments were used to carry out the best estimation against the current best practice techniques. It was verified a high proficiency in the estimation of N and Ca as well as achieving acceptable estimation for K, Mg, Fe and Zn. The calibrations for B, Cu and Mn were unsuccessful. Thus, research work done elucidates that the macro- and micronutrient monitoring through remote sensing is possible. This technique is real-time and rapid, non-destructive, cost-effective and environmentally friendly.

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Understanding the Crop-Climate Interaction Using Process-Based Simulation Models

13

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Abstract

Nowadays, outputs of the global climate models (GCMs) are extensively used as inputs for the crop simulation models (CSMs) to assess the impact of climate change on different agricultural crops. As the skills of GCMs and CSMs are not at per for decision-making at local scale, particularly in distract level due to the coarser resolution of GCMs and limited ability of representing the regional scenarios through crop models, so GCMs have to be evaluated to test its ability for reproducing the local scale climatic mean features and crop model has to be calibrated and validated with local scale experimental data before its application for climate change studies. The present chapter describes how the combined influence of climate and crop models are able to provide useful information for policy-making at subregional or local scale. First part, the centennial scale (1901–2000) district-wise rainfall change over West Bengal state for four distinct seasons and annual scale has been quantified using station data as well as GCM simulation. Based on the ability of GCMs to simulate observed rainfall, a group of better performing models is identified for North and South Bengal districts separately for using an input for any decision-making research. Percentage change (with respect to 1971–2000) of future annual monsoon and pre-monsoon season rainfall in different short-term (30 year) and long-term (100 year) periods revealed a decreasing trend of rainfall by 16–25% over South Bengal and 1–15% over North Bengal districts, while the winter and post-monsoon rainfall were projected to be increased by 60–117% and 1–15%, respectively, over North Bengal. Future temperature is always showing increasing trends in different time periods in different parts of the world as well as in Indian subcontinent. An attempt has been taken to investigate how the increasing trends of temperature, increasing/decreasing patterns of rainfall as well as

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elevated CO_2 can alter the productivity of rice crop over the Gangetic West Bengal region through a crop simulation model of rice, popularly known as 'ORYZA2000'. It is revealed that rice production decreases by about 10% with only 1 °C rise in temperature and current CO_2 level, while it increases by 10% under 1 °C rise of temperature and doubling CO_2 concentration. It is further noticed that productivity of rice will fall by 30% with a rise of temperature by 2 °C and doubling CO_2 level.

Keywords
West Bengal · Rainfall · ORYZA2000 · Future projection · GCM · RCP

13.1 Introduction

Climate scientists as well as agro-meteorologists are facing great difficulties to adequately estimate the amount of food grain requirement under the context of warming climate and increasing trends of global population. The climate scientists are struggling to provide reliable climate projection, as the model-based future projections are full of uncertainty. To quantify the actual production in the future, we must have prerequisite ideas of how much climate is going to be changed and how the different crop environments will respond in different changing environment particularly in the elevated temperature and CO_2 level. The agricultural system is considered as a complex system due to the exhibition of multiple interactions among climate, crop, and soil properties. Therefore, more focus is needed to understand how different climatic processes are influencing the growth and developmental of crops over different phenological stages. These detailed understanding of complex interaction between climate and crop in different growth stages may provide useful robust strategies for the policy-makers to implement suitable adaptation and mitigation options at district or local scale to combat climate change. Therefore, the whole chapter has been described into two different parts. The first part focuses the past climate change scenarios as well as its future projection over all districts of West Bengal state using the observational station data along with the simulations from GCMs, the second part demonstrates on estimating how the changing patterns of temperature, rainfall and CO_2 concentrations have impacted the growth and development of crops and hence amount of final productivity or yields.

Climate change emerged as one of the most important environmental burning issue, attracts global attention and needs to be addressed seriously to save the our environment. The Intergovernmental Panel on Climate Change (IPCC) has quantified the degree of climate change and its vulnerabilities over different scales. IPCC provides climate information in terms of different assessment reports published in different time interval. The recent two assessment reports are assessment report 4 (AR4) of 2007 and assessment report 5 (AR5) of 2013, where it was pointed out that developing countries are expected to be more vulnerable under climate change. Assessing the past and future scale climate change information at global scale using the GCMs is quite reasonable but comparatively smaller area; it is debatable due to their coarser resolution, so using GCM simulations for generating climatic information at local scale as well as using its simulations as an input for the crop simulation models to investigate the change of crop productivity may attract criticism. So as a case study, the present chapter has attempted to see how present-generation GCMs (CMIP5) are able to reproduce the observed seasonal rainfall over different North and South Bengal districts of West Bengal state. Based on their abilities, a group of better performing GCMs can be recommended to use as the inputs for the ORYZA2000 model for projecting rice yield variability under changing environment. On the basis of amount of rainfall received in different months, there are four major seasons in India: winter (December to February), pre-monsoon (March to May), monsoon (June to September) and post-monsoon (October and November). A major component of Asian summer monsoon is the Indian summer monsoon (ISM) that has a significant effect on the lives of more than 60% of the world's population (Wang and LinHo 2002). Almost 80% of the total annual rainfall in India is received by the ISM. Therefore, any alteration of the magnitudes of ISM may have strong effect on agricultural, hydrological and ecological systems resulting in stressed conditions of health and food security.

Over India, the annual and monsoon rainfall has shown decreasing trends, while an opposite sign was noticed in case of winter, pre-monsoon and post-monsoon seasons. The trend analysis of rainfall over West Bengal (WB) state of India indicated a significant increasing trend (91.0 mm/100 year) over Gangetic West Bengal (South Bengal) while over the sub-Himalayan WB (North Bengal) has shown a non-significant increasing trend (57.2 mm/100 year) during the period 1901–2003 (Guhathakurta and Rajeevan 2008). A similar type of study by Naidu et al. (2009) shows that the South Bengal has an increasing trend, while sub-Himalayan WB has as a decreasing trend of monsoon rainfall during the period 1871–2005. Sadhukhan et al. (2000) reported that there were no long-term trends found for the pre-monsoon rainfall over Gangetic WB and its neighbourhood during the period 1901–1992. On the other hand, Guhathakurta and Rajeevan (2008) reported a decreasing trend (non-significant) of 6.7 mm/100 year of pre-monsoon rainfall over South Bengal, whereas sub-Himalayan WB has shown an increasing trend of 10.5 mm/100 year. During the winter and post-monsoon seasons, the same study has reported a non-significant decreasing trend of rainfall for sub-Himalayan WB, whereas South Bengal has shown increasing trend in post-monsoon and decreasing trend in winter. Similarly, Chakraborty and Das (2016) reported that there is an increasing rainfall in post-monsoon season during 1901–2005 for most of the stations (except Krishnanagar, −47.67 mm), whereas a negative change of winter rainfall was estimated during the same period (except Alipore and Berhampur stations). The total annual rainfall over the state has an overall non-significant increasing trend (Das et al. 2018).

Seasonal rainfall distribution over WB shows that winter is the driest season of the year which contributes only 1–3.5% of the average annual rainfall. The hottest pre-monsoon season receives 8–17% of average annual rainfall, which is mostly associated with the pre-monsoon thunderstorm or ‘Norwester’ also popularly known as ‘Kalbaisakhi’. Bay of Bengal branch of the Indian Ocean monsoon brings 73–80% monsoon rain to the state from June to September. Monsoon rainfall has played a vital role in the last three decades during 1970–2000, there has been a significant increase in productivity of food grains over the state of WB, and the state now has a surplus of food (Raychaudhuri and Das 2005). The post-monsoon season shares 5–15% of average annual rainfall.

How crop production is sensitive to climate and its variability at regional and local level can be evaluated through crop models popularly known as crop-weather models. Crop-weather model is basically the relationship between crop variables with weather variables. This relationship is established through mathematical expression having independent parameters and response parameters (dependent). Crop-weather models can be classified into two broad categories. The first category is the statistical model, where a relationship can be established between crop data (LAI, yield, etc.) and weather data (rainfall, temperature, radiation, etc.) for the same common periods using statistical techniques such as regression that is known as empirical statistical model. The second category is the dynamical process-based model, which is known as crop simulation models (CSMs). CSMs establish a dynamical relationship between crop growth processes (photosynthesis, respiration or translocation) and environmental and management components (climate, soils and cultivation practices). Akponikpea et al. (2011) mentioned that CSMs can also be used to assess the impact of climate change and its variability on crop productivity and also provide some options for coping with this variability. In spite of huge application to explore many options, the available current crop models also attracted criticism due to inadequate representation of complex crop features in the extreme changing climate, incidence of new types of pest and diseases under changing climate, appearance of new modern crop varieties and innovative management practices. Another limitation of crop model is its inherent uncertainty to simulate the experimental yield leading to huge overestimation/underestimation, meaning excessive biases which resulted in its reliability to apply for decision-making and policy-making. Normally multi-level stakeholders or impact analysts want to see whether the models are able to reproduce the observable features adequately meaning the models are less erratic. But current-generation crop models unable to provide improved comprehensive idea about the model to the end users and policy-makers. Different models use different input processes to simulate their target parameter, providing different results, so any single model may not provide reliable information. So, multi-model ensemble techniques using large numbers of models may be able to provide more reliable future crop productivity under different future climate change scenarios. One example is using crop model under changing environment which is presented by Dias et al. (2016) where future yields of two varieties At362 and Bg357 over Mapalana region were assessed under extreme climate change scenario from RCP 8.5. The study revealed that grain yields of both varieties are expected to be decreased by 25%–35%, respectively, under the increasing temperature and solar radiation and decreasing rainfall. Another study by Swain and Yadav (2009) applied CERES-Rice model to investigate the higher yield variability of the long-duration (140 days) variety ‘Swarna’ as compared to the medium-duration (120 days) varieties (IR 36 and Lalat) under rain-fed condition of Kharagpur, India, using past 27 years (1974–2000) weather data. This study also showed an increased grain yield of up to 6% with increase in atmospheric CO_2 level by 100 ppm, while increase in average air temperature resulted in a decline in yield. Boling et al. (2004) used the rice growth model ORYZA2000 to analyse yield gaps and explore improved management options. It is to be mentioned that the ORYZA200 model has been extensively tested to predict crop performance under different environment and future climate change scenarios. Das et al. (2007) applied the ORYZA2000 model developed by Bouman (2001) over Gangetic West Bengal region of India and reported that only increase in temperature resulted in decreasing productivity but combined influence of elevated CO_2 and enhanced temperature can slow down the decreasing nature of productivity as CO_2 enrichment leading to increasing productivity. There has been a plenty of studies (Das and Lohar 2005; Rupa Kumar et al. 2002; Lohar and Pal 1995) based on the distribution of rainfall over the whole of WB and its neighbourhood in different seasons. During the last century, the climate of Gangetic West Bengal region has changed extensively. As for example, a study by Das and Lohar (2005) reported that the rainfall during post-monsoon season (October and November) has increased by 82% and winter (December to February) by 58% between the periods 1901–1930 and 1961–1990. The initial attempt to judge the performance of ORYZA2000 over Gangetic West Bengal region under different management conditions particularly under different nitrogen doses by Das et al. (2007) and under different irrigation regime by Majumder and Das (2018) was investigated. In both cases the model overestimated the rice yields. But there is a scattered picture of exact rainfall distribution and amount of rainfall change at district level. This study has been attempted to address the statistical distribution of rainfall over different districts of WB in annual and seasonal scale for a better understanding of the stakeholders, scientific community and for the general public. Integrating the climatic information from climate simulation on rice production through crop simulation model is also assessed through simulation model through increasing the temperature, increasing the level of CO_2 and combined effect on elevated temperature as well as elevated CO_2 to see the sensitivity of rice productivity for a particular variety, IET-4786, using ORYZA2000 over new alluvial zones of West Bengal.

13.2 Description of GCMs and CSMs

The present chapter deals with two components. The first component is to construct climate change scenarios using the sophisticated tool of recent-generation global climate models (GCMs), and the second part is to assess the crop production using the processed-based crop simulation models under the changing environment as generated by the GCMs, and finally it has been applied over the West Bengal state as a case study.

13.2.1 Description of GCMs

The definition and some limitations of GCMs have been discussed in this section. Global climate models are also called as general circulation models. Both are abbreviated as GCMs. In general GCMs are comprised of fundamental concepts (laws) of climate systems leading to general circulation of a planetary atmosphere or ocean. It is a numerical model representing the physical processes of the earth, atmosphere and ocean. It is a modern tool used to investigate the response of elevated greenhouse gases in the atmosphere that can alter earth's weather and climate system. How water vapour is contained in the atmosphere, distribution of clouds, change of incoming and outgoing solar radiation, ocean circulation, changes of ice and snow cover on the sea can regulate the earth climate system can also be understood through analysing the GCM data.

The skills of climate models are assessed through its ability to reproduce the observed features of past and recent climate (Randall et al. 2007). The observed local scale past and current features are incorporated into the GCMs through the process of parameterization. Some important sub-grid-scale processes such as cloud formation/ processes, radiative processes and boundary layer processes are represented into the GCMs through mathematical equations within the model grids. Present-generation model resolutions are still to be considered coarser; the limited grids do not resolve many of the small-scale processes adequately. In such a case, the parameterization is needed. Many meteorological parameters like temperature, pressure, wind speed and humidity can be represented by the mathematical equations, which defined the state of the atmosphere. All these mathematical expressions can then be converted to a programming language and finally solve those equations numerically using discrete time step through a computer, which is called numerical weather prediction (NWP). Through the passage of time, the horizontal resolution used in state-of-the-art climate models has improved a lot from the IPCC first assessment report (FAR 1990) to the recent assessment reports published in 2013. How the GCM performance over a smaller region like the Gangetic West Bengal of eastern part of India has improved starting from second assessment report (SAR) of 1995 to fourth assessment report (AR4) has been investigated by Das et al. (2012). It is to be mentioned that earlier-generation (in 1990) GCMs used to have an average horizontal resolution of about 500 km, whereas some has improved manifolds with an average resolution of ~60 km (https://scied.ucar.edu/longcontent/climate-modeling) of some high-resolution models in the recent generation (in 2013). Different models based on different emission scenarios, radiative forcing and different types of parameterization schemes are able to produce different realization of rainfall, temperature and other climatic elements. So estimating current and future climate change information using single GCM may not reflect the true picture at subregional or local scale. Therefore, generation of climate change scenarios using large numbers of GCMs is recommended to avoid inherent biases and affinity to represent some spatial features by each individual GCM. It is also recommended to choose some better performing GCMs and make a multi-model ensemble for future climate projection from the wide range of GCMs available in CMIP5.

The aim of GCMs is to provide the outputs of different climatic parameters like rainfall, temperature, radiation, wind, radiation, etc. at varying horizontal resolution typically ranging 100–200 km with multiple vertical layer (40–60 layers) both in the atmosphere and ocean. It is to be also mentioned that the GCMs also provide their simulations for the impact analysis, policy-makers or multiple level stakeholders with temporal resolution ranging from annual, monthly, daily to a typical time step of 30 min.

13.2.2 Description of CSMs

Similar to climate model, a detailed description and limitation of recent-generation crop model has been discussed in this section. Crop simulation models can help to understand the growth and development of real crop system and also provide some way out how to enhance productivity under different climatic conditions (Penning de Vries 1977). In addition, it is also used to judge the crop performance under stressful environmental conditions. For the purpose of regional development and agricultural planning where efficient human resources or skilled personnel are limited particularly in the developing countries, the crop models can be effectively used (Van Keulen and Wolf 1986) with less amount of natural resources to achieve optimal production. Nowadays availability of land, water and other natural resources for agricultural activities are limited; on the other hand, multi-level stakeholders need to have huge up-to-date agricultural information for local scale decision-making for implementing local scale developmental activities. So in these cases, crop simulation model can provide useful information within a short period of time compared to conventional procedures of getting information which is time-consuming. For example, potential (maximum) crop production of each district can be obtained through crop simulation model using their long-term weather data. Therefore, a decision-maker can easily estimate what is the productivity gap by subtracting the real-time field-level production from the potential production obtained from model. To meet the demand of a policy-maker, the scientists need to develop the decision support system for agrotechnology transfer (DSSAT). A group of international scientists who were cooperating in the International Benchmark Sites Network for Agrotechnology Transfer project (IBSNAT 1993; Tsuji 1998; Uehara 1998; Jones et al. 1998) developed DSSAT model having facility to investigate performance of many agronomic crops (16 different crops). The performance of all 16 different crops was incorporated into packages of practice without source code (programming languages); hence, it is a software having facilities to evaluate its performance in multiple locations with different purposes (Jones et al. 2003).

The output of climate model can be used as an input in crop model to investigate multiple interactions. A common use of crop model is to see the impact of climate change on crop productivity. How different physiological processes of crop respond under different elevated temperature and CO_2 level is also assessed. Which phenological stages of the crops are highly sensitive to which meteorological parameters is also to be judged. Apart, it can also be used to optimize the use of nitrogen, water use and other agronomic practices like the planning of optimal date of sowing and harvesting, date of irrigation and application of pesticides and herbicides, etc. Although the model is running in point location, it can be scaled up to larger regions. Another group of scientists also used statistical models instead of simulation models. It is to be mentioned that statistical models lag time components and use only the climates and atmospheric conditions of today. Therefore such model cannot be able to investigate the interactions between crop genotype and environmental and management effect which are important for decision-making. Future crop behaviour is heavily dependent on the complex interactions between many crop, soil, weather and management factors. The process-based crop models are always not able to show decreasing trends of productivity under elevated temperature, resulting in simulation of more yields indicating overestimation where the region is experiencing more frequent hot days during the growing season. On the other hand, increasing CO_2 can limit the loss of water through the stomata of plant leaves, meaning transpiration of plants. Less transpiration results in more biomass production indicating more yields.

As mentioned above, DSSAT models have been used over India in different agricultural activity, viz. for crop management (Jintrawet 1995; Alagarswamy et al. 2000; Salam et al. 2001; Singh et al. 1994), for optimizing the fertilizer application (Godwin et al. 1994), for irrigation scheduling (Hundal and Kaur 1997), for pest monitoring (Pinnschmidt et al. 1995; Luo et al. 1997), for studying the impact of climate change (Singh and Godwin 1990; Lal et al. 1998, 1999; Jinghua and Erda 1996; Luo et al. 1995, 1998), for also assessing the impact of climate variability (Gadgil et al. 1999, Alocilja and Ritchie 1990), for yield prediction (Singh et al. 1999; Kaur and Hundal 1999) and for sustainable development (Singh et al. 1999a, b), whereas the lowland rice growth models (ORYZA2000) developed by Bouman (2001) have mainly focused on rice crop which has many components of application starting from optimization of suitable dose of nitrogen and irrigation application to studying the effect of climate change on rice production under increased temperature and CO_2 level.

13.2.3 Multi-model Ensemble Simulation

Based on various forcing of the climate model, different outputs for many meteorological parameters are generated. Single model produces different scenarios of climatic states making confusion to the user which one is suitable for their application. To provide a unique guideline, several studies (Das and Lohar 2005, 2012, 2017; Das et al. 2016; Akhter et al. 2016, 2018; Meher et al. 2017) concluded that it is better to use a group of good performing model instead of using a single model which is technically known as multiple model ensembles.

Different models use different physical and biological processes resulting in different possible outputs. Therefore, through the multi-model ensemble simulations, a wide range of possible outcomes can be generated on the basis of different realization considering the model. This wide range of model simulation basically provides a range of uncertainty of model simulation. On the contrary to climate model, the crop simulation offers a substantially lower computational challenge, so making ensemble using large numbers of models may be easier compared to climate model. As different models produce different outputs, determining multi-model averages is a promising practice than to use a single-model output. It is advisable to use multiple crop models to simulate same predefined field experiment to see how results differ from model to model because of representing the same growth and development processes into the model through different mathematical expressions and assumptions. Undoubtedly, it is to be mentioned that the model results differ from experimental results because of the following reasons: first, all the yield-affecting factors starting from the incident of pest and diseases to different types of stress which arise due to nutrient and water availability in different phenological stages are not adequately represented in the model. Second, all short of input management data required for crop model with adequate quality is not generated at farm level which produces erroneous model results for testing its reliability. Third, models that are run using the data for a point location, when comparing the model results with larger regional scale yield data, may produce error through upscaling interpolation techniques. Fourth, false incorporation of extreme weather data or outlier for observational crop management data may produce mismatching results. Finally, a suitable weather generator from the climate model simulation is required to feed the daily weather inputs required for crop model for all variables. More attention would be paid to the simulation of crop and climate models by the government agency if uncertainty ranges are being provided vis-a-vis the model simulation. It is essential to develop formal protocols for reporting uncertainties in crop model results similar to climate model for better understanding for farming community and stakeholder. Therefore, it seems that we should operate multiple models to simulate the same process to compare the results among each other for providing appropriate recommendations for farming community through which we will be able to deliver more robust and usable information for everyone from farmers to policy-makers with high level of certainty.

13.3 Basic Data Set Requirement for Climate and Crop Models

This section deals with the basic data requirement for running the crop model and analysing the GCM simulation for the purpose of providing input information for any impact assessment model including crop. As the present chapter is focusing on analysing the outputs of GCM simulation towards assessing the impact of climate change on rice production over a location of West Bengal State, we first described the geographical and climatological extent of this state with numbers of districts falling within North or South Bengal. The state is extending from 21.20°N to 27.32° N latitude and 85.50°E to 89.52°E longitudes in the eastern part of India. Six districts from the northern part, namely, Darjeeling, Jalpaiguri, Cooch Behar, North Dinajpur, South Dinajpur and Malda, collectively named as ‘North Bengal’ and the rest of the 13 districts of southern part, namely, Birbhum, Murshidabad, Bardhaman, Nadia, Purulia, Bankura, Hooghly, North 24 Parganas, West

Midnapore, Howrah, Kolkata, South 24 Parganas and East Midnapore, together termed as ‘South Bengal’ are considered for the present study. For the purpose of analysis of district-level rainfall change, monthly total rainfall data during the period 1901–2000 for 19 districts of WB state have been collected from the India Meteorological Department (IMD). In this present study, time series analysis is carried out for each district and their regional average (averaged over all available districts) both for North and South Bengal. For quantifying district-level rainfall change trend during 1901–2000, we used Mann Kendall trend test and Sen’s slope estimator test.

ORYZA2000 is one of the ecophysiological models which simulates growth and development of rice under lowland, upland and aerobic rice ecosystems. The model works under potential, water-limited, nitrogen-limited and nitrogen-water-limited conditions. It has been calibrated and validated for almost 18 popular rice varieties in 15 locations throughout Asia. Still, it is not reached to it optimal capacity to use it for operational purpose particularly in different homogeneous or agro-climatic zones which demands more trail of testing over different zones with different varieties as per the normal practices in the farm level. One of the most important assumptions for the ORYZA2000 model is its inability to assess its yield variations due to other stresses (occurrence of pest and diseases) apart from moisture and nitrogenous fertilizer. It uses four different types of input data files: (i) experimental management data file, (ii) crop data file, (iii) soil data file and (iv) weather data file. For the purpose of impact study using ORYZA2000 model, the six numbers of weather variables are collected from Bidhan Chandra Krishi Viswavidyalaya’s (BCKV) observatory, located at Mohanpur campus. Crop management data have also been collected from the experimental farm of BCKV. The details of field experiment which was considered for the model validation and calibration are replication, 3; number of treatment, 15; plot size, 5 m by 3 m; spacing, 20 cm by 10 cm; total number of plot, 45; net plot size, 4 m by 2 m; seed rate, 15 kg ha^{-1} for hybrid and 60 kg ha^{-1} for H.Y.V; and number of varieties, 5.

13.4 Historical Rainfall Change Using Station Data

13.4.1 Temporal Rainfall Change

In general rainfall change trends during 1901–1930 period for North Bengal districts except Cooch Behar indicate a positive increasing rainfall, while the South Bengal district like Birbhum, Murshidabad and Purulia districts recorded positive trend, and the remaining ten districts showed the negative trend. The long-term linear trend analysis (1901–2000) of winter rainfall showed all districts of North Bengal, and six districts of South Bengal recorded the positive change, while the remaining seven districts of South Bengal recorded a negative change. It is interesting to note that the monsoon rain during 1901–2000, in the North Bengal Darjeeling, Cooch Behar and Malda districts, recorded an increasing trend in rainfall, whereas Cooch Behar showed maximum rainfall trend (+413.76 mm), and remaining three districts recorded decreasing trend. In South Bengal, only one district Nadia (−38.14 mm) showed declining trend, whereas in both North and South Bengal, South 24 Parganas recorded maximum increasing trend of rainfall (+487.47 mm).

On the other hand, the annual rainfall during 1901–2000, in the North Bengal Jalpaiguri (−134.28 mm) and South Dinajpur (−59.54 mm) districts, recorded a decreasing trend in rainfall, whereas remaining four districts recorded increasing trend. In the South Bengal, only Bardhaman (−52.18 mm) and Nadia (−161.60 mm) districts showed decline trend, whereas in both North and South Bengal, South 24 Parganas recorded maximum increasing trend of rainfall (+671.73 mm).

13.4.2 Spatial Distribution of Rainfall

Distribution of mean rainfall in different short-term and long-term periods is not uniform. For example, the monsoon rainfall (Fig. 13.1) during 1901–1930 showed a decreasing trend in Birbhum, Murshidabad, Nadia, some part of Darjeeling, Cooch Behar and North Dinajpur districts, while the southern part of Bengal like from Purulia to South 24 Parganas and some part of North 24 Parganas showed the increasing trend (101.5–212.1 mm/30 years). During the long-term period from 1901 to 2000, only two districts, namely, Cooch Behar and a very small part of the South 24 Parganas, showed the highly increasing trend. In Bengal during this time period, all districts showed the increasing trend except Jalpaiguri and some parts of the South Dinajpur, Nadia and Bardhaman districts. The increasing trend of West Midnapore, East Midnapore, Howrah and South 24 Parganas, some part of the North 24 Parganas, Hooghly, Birbhum, Murshidabad, Darjeeling and Jalpaiguri was from 164.1 to 326.6 mm/100 years. Similarly the spatial distributions of annual rainfall change trends during different time periods are shown in Fig. 13.2.

13.5 Evaluation of GCMs Performance

How the 42 numbers of CMIP5 GCMs (whose description was provided in Table 13.1) were able to simulate the observed rainfall features over the whole West Bengal and separately over North and South Bengal was evaluated through four different approaches which are (i) comparison of seasonal cycles, (ii) comparison of long-term trends, (iii) comparison of Taylor plots and (iv) comparison of spatial patterns. Comparison of different statistical measures and trends for different GCMs over North and South Bengal districts was shown in Tables 13.2 and 13.3. Majority of the models were unable to reproduce the observed increasing trends of annual and monsoon season adequately over North and South Bengal regions. Based on long-term trends and values of statistical indices, we have seen that some models overestimated the mean observed seasonal cycles, whereas some underestimate the same, but all models underestimate the magnitudes of annual and monsoon rainfall compared to observation. To select how

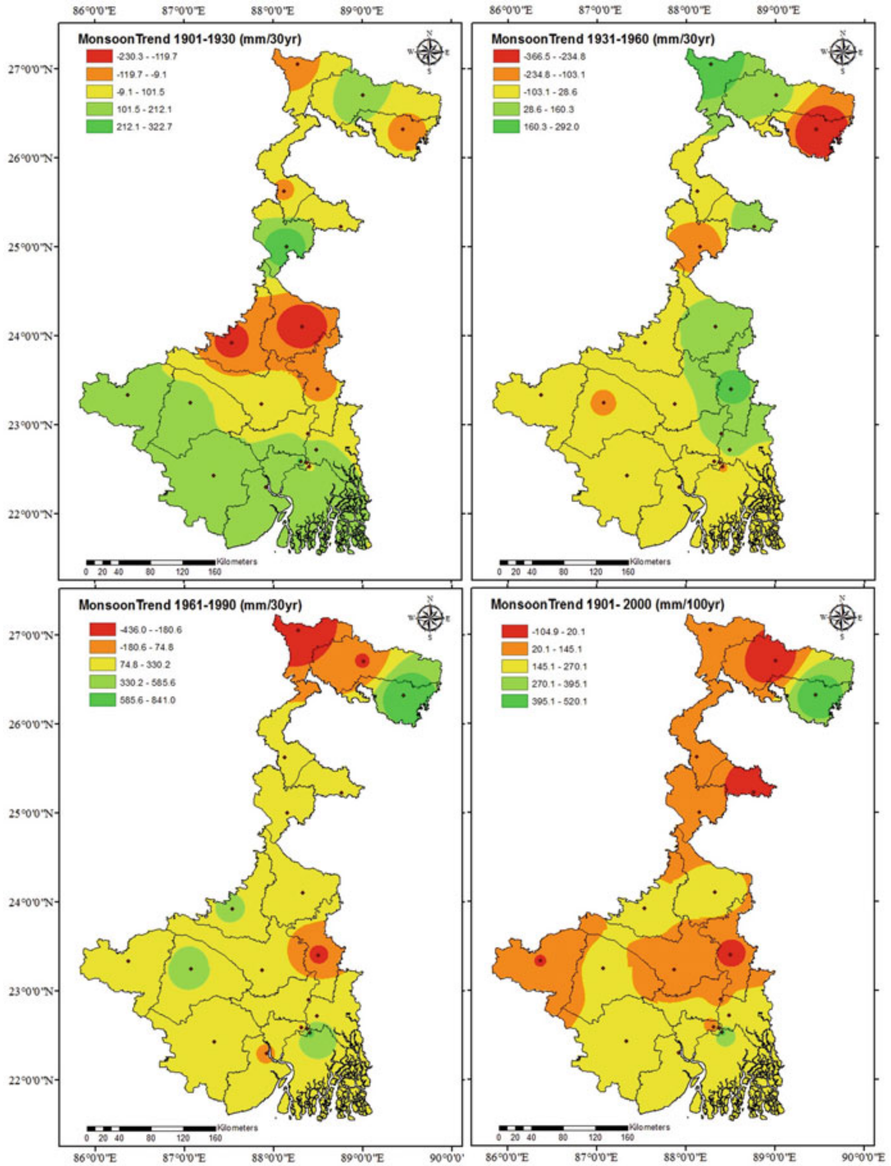

Fig. 13.1 Spatial variations of monsoon season mean rainfall in different time periods

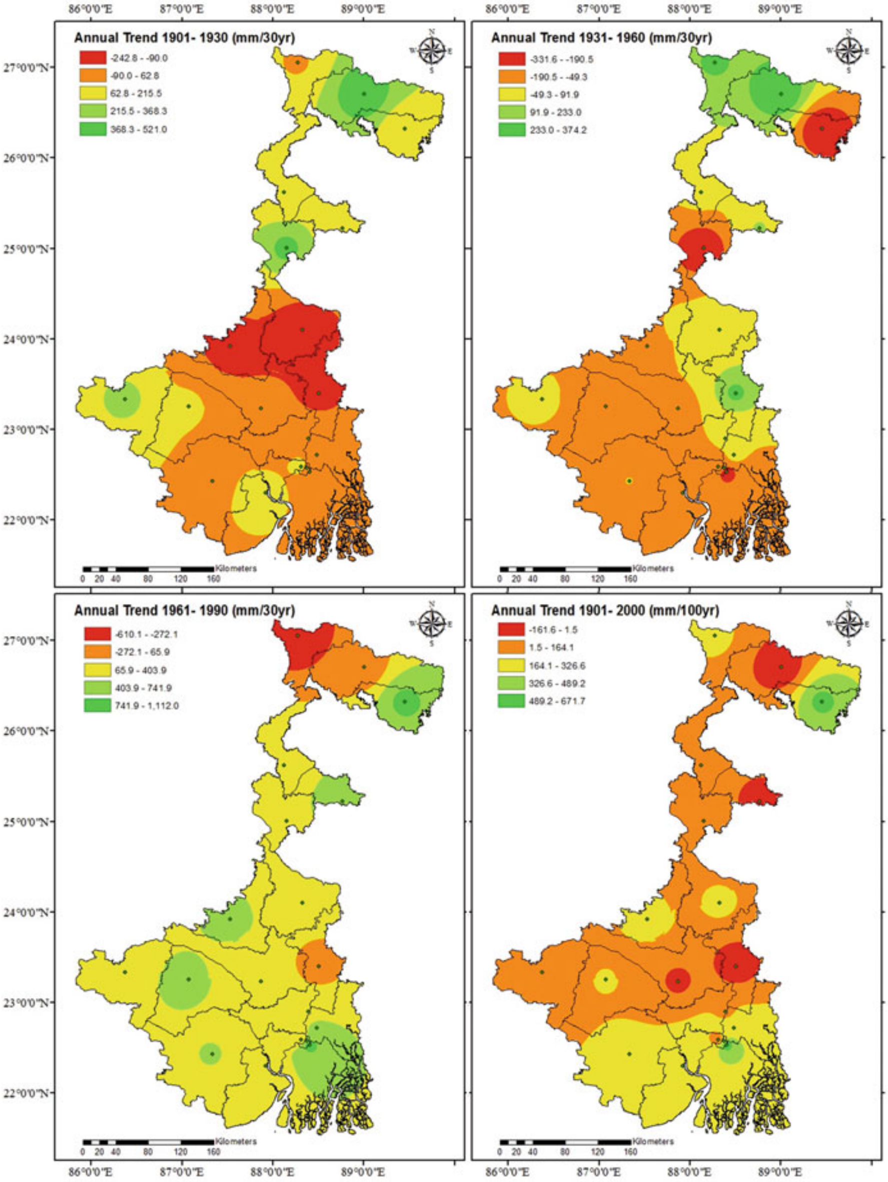

Fig. 13.2 Spatial variations of monsoon season mean rainfall in different time periods

Table 13.1 All CMIP5 GCMs taken in this study

	Model	Centre	Resolution (Lon. × Lat.)
1	ACCESS1-0	Commonwealth Scientific and Industrial Research Organization-Bureau of Meteorology (CSIRO-BOM), Australia	1.88 × 1.25
2	ACCESS1.3		
3	bcc-csm1-1	Beijing Climate Center, China Meteorological Administration	2.80 × 2.80
4	bcc-csm1-1-m		1.12 × 1.12
5	BNU-ESM	College of Global Change and Earth System Science, Beijing Normal University, China	2.80 × 2.80
6	CanESM2	Canadian Centre for Climate Modelling and Analysis	2.80 × 2.80
7	CCSM4	National Center of Atmospheric Research, USA	1.25 × 0.94
8	CESM1-BGC	Community Earth System Model Contributors	1.25 × 0.94
9	CESM1-CAM5		
10	CMCC-CESM	Centro Euro-Mediterraneo sui Cambiamenti Climatici	3.75 × 3.71
11	CMCC-CM		0.75 × 0.75
12	CMCC-CMS		1.88 × 1.87
13	CNRM-CM5	National Centre of Meteorological Research, France	1.40 × 1.40
14	CNRM-CM5-2		
15	CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organization Queensland Climate Change Centre of Excellence, Australia	1.80 × 1.80
16	EC-EARTH	EC-EARTH consortium	1.13 × 1.12
17	FGOALS-g2	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences	2.80 × 2.80
18	FGOALS-s2		2.80 × 1.70
19	FIO-ESM	The First Institute of Oceanography, SOA, China	2.81 × 2.79
20	GFDL-CM3	NOAA Geophysical Fluid Dynamics Laboratory, USA	2.50 × 2.00
21	GFDL-ESM2G		
22	GFDL-ESM2M		
23	GISS-E2-H	NASA Goddard Institute for Space Studies, USA	2.50 × 2.00
24	GISS-E2-H-CC		
25	GISS-E2-R		

(continued)

Table 13.1 (continued)

	Model	Centre	Resolution (Lon. × Lat.)
26	HadCM3	Met Office Hadley Centre, UK	3.75 × 2.50
27	HadGEM2-AO		1.88 × 1.25
28	HadGEM2-CC		1.88 × 1.25
29	HadGEM2-ES		1.88 × 1.25
30	INMCM4	Institute for Numerical Mathematics, Russia	2.00 × 1.50
31	IPSL-CM5A-LR	Institute Pierre Simon Laplace, France	3.75 × 1.80
32	IPSL-CM5A-MR		2.50 × 1.25
33	IPSL-CM5B-LR		3.75 × 1.80
34	MIROC5	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo) and National Institute for Environmental Studies	1.40 × 1.40
35	MIROC-ESM		2.80 × 2.80
36	MIROC-ESM-CHEM		2.80 × 2.80
37	MPI-ESM-P	Max Planck Institute for Meteorology, Germany	1.88 × 1.87
38	MPI-ESM-LR		
39	MPI-ESM-MR		
40	MRI-CGCM3	Meteorological Research Institute, Japan	1.10 × 1.10
41	NorESM1-M	Norwegian Climate Centre, Norway	2.50 × 1.90
42	NorESM1-ME		

models are able to simulate seasonally observed rainfall, we calculated the spatial correlation considering the 19 district values during the period 1901–2000, but the results are not shown.

13.5.1 Selection of Better GCMs for North Bengal

On the basis of trends and statistical indices (Table 13.2), we noticed that the 11 models, namely, CCSM4, CESM1-BGC, CESM1-CAM5, CMCC-CM, CMCC-CMS, inmcm4, MIROC5, MPI-ESM-LR, MPI-ESM-MR, NorESM1-M and NorESM1-ME, have shown the high value of agreement and low value error

Table 13.2 Statistical indices between the seasonal cycles of observation and model simulation along with the linear trends during the period of 1901–2000 over North Bengal

		Indices from seasonal cycles				Trends (mm/100 year) during 1901–2000				
	Model name	d-index	corr	nrmse	pbias	Annual	JJAS	DJF	MAM	ON
	OBS	1	1	0	0	88.4	68.0	6.9	20.5	−6.0
1	ACCESS1-0	0.98	0.98	25.90	−7.60	−101.6	−101.0	−17.3	25.0	−9.0
2	ACCESS1-3	0.92	0.90	46.90	−13.10	−109.8	−144.6	−12.4	52.0	−5.6
3	bcc-csm1-1	0.77	0.85	73.60	−46.00	−6.0	1.0	−23.8	−28.4	43.0
4	bcc-csm1-1-m	0.67	0.97	81.00	−50.70	116.7	40.3	17.2	18.4	41.2
5	BNU-ESM	0.86	0.98	58.00	−40.00	−49.9	−48.2	18.0	−13.2	−5.5
6	CanESM2	0.86	0.95	61.30	−45.20	−130.1	−144.8	8.6	9.7	−2.8
7	CCSM4	0.94	0.97	39.20	−20.70	62.8	39.9	−7.1	−6.0	35.9
8	CESM1-BGC	0.95	0.96	38.40	−19.70	41.9	5.4	−12.8	65.2	−17.2
9	CESM1-CAM5	0.98	0.96	25.60	3.00	40.3	−44.8	16.8	49.2	20.1
10	CMCC-CM	0.96	0.95	36.20	−20.50	35.0	19.3	21.2	4.7	−8.8
11	CMCC-CMS	0.94	0.97	39.90	−25.20	84.3	53.0	−5.3	12.4	22.6
12	CNRM-CM5	0.92	0.99	44.90	−27.00	−201.4	−107.3	−11.0	−55.8	−27.3
13	CSIRO-Mk3-6-0	0.77	0.86	76.10	−52.10	−16.2	−23.0	−4.3	4.2	7.2
14	EC-EARTH	0.83	0.98	62.80	−42.50	135.3	101.6	2.3	9.7	22.0
15	FGOALS_g2	0.62	0.96	92.70	−63.60	106.5	42.7	12.8	35.0	15.7
16	FIO-ESM	0.86	0.94	59.80	−41.00	−21.8	−31.0	3.8	12.6	−6.0
17	GFDL-CM3	0.80	0.97	65.70	−42.00	−166.7	−115.7	14.6	−8.6	−56.2
18	GFDL-ESM2G	0.93	0.98	42.80	−30.20	39.4	73.9	13.1	−21.0	−28.5
19	GFDL-ESM2M	0.95	0.98	36.10	−23.60	−18.1	−62.7	5.6	20.5	18.8
20	GISS-E2-H-1	0.95	0.91	41.50	−4.00	−391.9	−402.5	2.6	4.4	4.6
21	GISS-E2-H-2	0.95	0.90	42.40	−8.80	−468.8	−434.3	−7.8	−4.4	−21.9
22	GISS-E2-H-3	0.93	0.92	59.00	21.70	−311.7	−283.1	−3.7	−22.2	−2.7
23	GISS-E2-H-CC	0.95	0.91	41.30	−12.60	−169.8	−154.2	2.1	−15.5	−4.5

24	GISS-E2-R-1	0.77	0.89	72.30	−46.90	−143.3	−159.1	1.7	3.7	9.9
25	GISS-E2-R-2	0.75	0.88	75.60	−49.20	−246.2	−227.8	4.3	1.0	−22.6
26	GISS-E2-R-3	0.88	0.90	56.80	−33.20	−77.0	−98.2	3.9	14.8	2.4
27	GISS-E2-R-CC	0.77	0.90	72.10	−46.90	−69.4	−122.3	4.9	22.9	25.8
28	HadGEM2-AO	0.96	0.98	33.40	−14.20	−94.4	−157.1	−2.2	42.2	24.4
29	HadGEM2-CC	0.97	0.98	30.30	−11.90	−251.8	−191.5	−4.5	−46.3	−6.3
30	HadGEM2-ES	0.96	0.98	32.40	−15.10	−179.5	−152.0	−7.4	−8.5	−12.3
31	inmcm4	0.93	0.98	41.20	−23.40	77.7	61.0	−3.5	−3.0	24.1
32	IPSL-CM5A-LR	0.63	0.79	91.80	−61.50	−29.9	−17.9	−7.7	9.4	−13.7
33	IPSL-CM5A-MR	0.63	0.93	92.00	−65.30	−72.5	−45.5	−6.7	−2.5	−19.5
34	IPSL-CM5B-LR	0.55	0.68	104.00	−67.90	−67.8	−102.4	21.4	18.0	−6.3
35	MIROC5	0.98	0.96	28.70	7.70	192.2	118.5	−2.2	60.4	15.4
36	MIROC-ESM	0.81	0.97	65.40	−42.40	−66.4	−48.7	−27.7	30.0	−19.3
37	MIROC-ESM-CHEM	0.80	0.96	66.10	−42.70	23.9	−9.1	0.8	50.2	−18.5
38	MPI-ESM-LR	0.99	0.99	21.80	−15.10	15.4	−37.9	8.0	16.7	28.4
39	MPI-ESM-MR	0.98	0.98	26.80	−18.80	31.2	37.5	−18.7	17.9	−4.4
40	MRI-CGCM3	0.62	0.86	93.90	−65.10	−97.8	−26.8	−22.9	−29.0	−20.5
41	NorESM1-M	0.98	0.97	27.50	−11.70	78.4	58.7	43.2	−8.7	−11.2
42	NorESM1-ME	0.98	0.97	26.90	−10.70	82.1	63.0	−3.1	10.9	15.2

Table 13.3 Statistical indices between the seasonal cycles of observation and model simulation along with the linear trends during the period of 1901–2000 over South Bengal

SL	Model name	Indices from seasonal cycles				Trends (mm/100 year) during 1901–2000				
		D	r	nrmse	pbias	Annual	JJAS	DJF	MAM	ON
	OBS	1	1	0	0	143.1	136.7	0.9	−13.6	22.6
1	ACCESS1-0	0.91	0.93	71.6	26.7	−10.5	−32.4	0.4	24.6	−4.6
2	ACCESS1-3	0.84	0.76	66.7	−23.4	−12.6	−110.1	38.1	51.6	5.1
3	bcc-csm1-1	0.79	0.90	71.0	−43.2	38.7	66.8	−51.2	−9.4	31.2
4	bcc-csm1-1-m	0.69	0.94	74.0	−33.2	117.1	18.4	41.2	6.7	49.7
5	BNU-ESM	0.83	0.98	63.6	−44.4	83.6	69.7	3.0	−13.8	25.8
6	CanESM2	0.96	0.98	34.1	−22.6	−35.0	−46.1	5.9	−3.1	8.3
7	CCSM4	0.98	0.99	24.2	−8.3	46.2	31.8	−0.1	−10.2	24.6
8	CESM1-BGC	0.98	0.99	25.0	−9.7	57.5	41.3	−11.3	19.2	6.4
9	CESM1-CAM5	0.96	0.98	34.5	−15.7	83.7	30.7	16.7	19.6	16.8
10	CMCC-CM	0.88	0.94	56.3	−37.9	−48.1	−25.2	5.9	−18.2	−10.4
11	CMCC-CMS	0.91	0.95	48.6	−29.6	13.9	6.4	−9.1	9.5	7.0
12	CNRM-CM5	0.97	0.98	27.7	−8.8	−104.9	−23.8	−22.4	−48.0	−11.8
13	CSIRO-Mk3-6-0	0.91	0.84	55.6	−13.2	20.1	22.6	−8.4	1.5	4.2
14	EC-EARTH	0.98	0.96	28.1	−3.6	19.1	−3.3	−0.9	−1.7	25.6
15	FGOALS_g2	0.78	0.96	72.6	−48.7	66.1	32.6	−0.6	19.3	14.4
16	FIO-ESM	0.82	0.97	65.0	−42.4	22.6	30.0	6.4	15.9	−30.0
17	NOAA1	0.99	0.98	17.3	−1.0	−127.2	−103.8	6.1	5.2	−34.1
18	NOAA2	0.95	0.97	40.9	−31.0	−25.4	−28.8	6.4	0.7	−5.9
19	NOAA3	0.92	0.97	48.1	−34.3	−52.7	−73.2	−7.9	4.4	24.1
20	GISS-E2-H-1	0.93	0.89	50.6	−21.7	−78.2	−106.3	3.3	17.9	7.2
21	GISS-E2-H-2	0.92	0.88	53.0	−23.6	−234.0	−223.1	−2.3	7.2	−15.4
22	GISS-E2-H-3	0.92	0.91	65.0	5.6	−131.4	−130.6	−1.4	−0.6	1.2
23	GISS-E2-H-CC	0.91	0.87	55.9	−28.2	−101.6	−109.8	0.7	−2.2	8.9

24	GISS-E2-R-1	0.80	0.84	75.6	−50.5	−95.1	−102.4	0.7	2.6	3.6
25	GISS-E2-R-2	0.78	0.82	78.4	−52.3	−131.8	−116.5	0.1	−0.7	−14.6
26	GISS-E2-R-3	0.89	0.87	59.2	−34.8	−19.4	−36.9	1.0	12.4	3.9
27	GISS-E2-R-CC	0.77	0.84	78.1	−52.6	−46.1	−76.2	−0.3	18.0	12.3
28	HadGEM2-AO	0.92	0.91	63.3	14.2	138.9	51.7	11.1	25.2	52.4
29	HadGEM2-CC	0.94	0.90	49.3	1.4	−39.0	19.3	−4.6	−38.6	−14.3
30	HadGEM2-ES	0.94	0.91	53.4	9.3	−43.1	−59.7	13.7	4.8	−2.4
31	inmcm4	0.97	0.94	32.4	−6.6	45.6	37.7	−11.4	−3.0	23.7
32	IPSL-CM5A-LR	0.74	0.89	80.9	−54.3	−55.8	−42.8	−3.6	3.1	−11.9
33	IPSL-CM5A-MR	0.92	0.92	48.7	−29.5	−87.1	−31.7	−16.0	−3.8	−37.6
34	IPSL-CM5B-LR	0.56	0.66	106.5	−68.6	−22.9	−14.2	1.3	−1.2	−8.7
35	MIROC5	0.90	0.93	72.9	36.4	−89.6	−119.6	2.8	8.7	19.2
36	MIROC-ESM	0.92	0.97	48.1	−35.1	−61.5	−34.5	−21.0	−16.0	9.8
37	MIROC-ESM-CHEM	0.91	0.96	50.7	−35.3	−111.7	−67.4	6.1	−26.4	−23.1
38	MPI-ESM-LR	0.91	0.96	50.4	−33.7	49.0	15.0	3.5	5.1	25.0
39	MPI-ESM-MR	0.90	0.98	50.5	−35.2	4.1	24.5	−12.0	−2.8	−4.7
40	MRI-CGCM3	0.53	0.60	108.5	−67.6	2.7	75.1	−37.9	−9.9	−25.7
41	NorESM1-M	0.92	0.97	47.3	−30.4	47.0	27.9	40.2	15.7	−33.7
42	NorESM1-ME	0.92	0.97	45.6	−29.8	22.0	−18.7	5.3	14.6	19.5

indices over North Bengal region for annual rainfall simulation. So all these 11 GCMs or any suitable combination of these 11 models can be used for the future projection of rainfall over the North Bengal. Similarly, the following GCMs are selected for developing the future projection rainfall change scenarios for any decision-making and long-term developmental plan over the study area:

12 GCMs in case of monsoon season, namely, bcc-csm1-1, bcc-csm1-1-m, CCSM4, CESM1-BGC, CMCC-CM, CMCC-CMS, GFDL-CM3, inmcm4, MIROC5, MPI-ESM-MR, NorESM1-M and NorESM1-ME

15 GCMs in case of pre-monsoon, namely, CESM1-CAM5, CSIRO-Mk3-6-0, FIO-ESM, GFDL-ESM 2-M, GISS-E2-H-1, GISS-E2-R-1, GISS-E2-R-2, HadGEM2-AO, IPSL-CM5A-LR, MIROC5, MIROC-ESM, MIROC-ESM-CHEM, NorESM1-ME, MPI-ESM-LR and MPI-ESM-MR

12 GCMs in case of post-monsoon season, namely, FIO-ESM, GFDL-CM3, GFDL-ESM 2G, GISS-E2-H-2, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM, MIROC-ESM-CHEM, MRI-CGCM3, NorESM-1, MPI-ESM-MR and IPSL-CM5B-LR

4 GCMs in case of winter season, namely, CESM1-CAM5, GFDL-ESM-2G, GFDL-ESM-2 M and NorESM1-ME

Towards selecting the season-wise GCMs, more attention has been given to compare the trends both on observation and model along with values of spatial correlation.

13.5.2 Selection of Better GCMs for South Bengal

Similar to North Bengal, based on the different statistical measures as shown in Table 13.3, the models, namely, CCSM4, CESM1-BGC, CESM1-CAM5, CMCC-CMS, EC-EARTH, inmcm4, MPI-ESM-LR, NorESM1-M and NorESM1-ME have shown better performances through their high values of agreement index and lower values of error indices. Therefore, either all the nine models or any combination of these nine models can be used for creation of future rainfall change scenarios over the South Bengal apart from using those any impact research. The following are selected for future projection of rainfall based on the values of trends and spatial correlations:

10 GCMs in case of monsoon season, namely, bcc-csm1-1, bcc-csm1-1-m, CCSM4, CESM1-CAM5, CMCC-CMS, FIO-ESM, HadGEM2-AO, MRI-CGCM3, MPI-ESM-LR and NorESM1-M

10 GCMs in case of pre-monsoon, namely, bcc-csm1-1, CCSM4, CNRM-CM5, GISS-E2-H-3, GISS-E2-R-2, IPSL-CM5A-MR, MIROC-ESM, MIROC-ESM-CHEM, MPI-ESM-MR and MRI-CGCM3

8 GCMs in case of post-monsoon season, namely, bcc-ccm1-1, CCSM4, CSM1-CAM5, GFDL-ESM 2M, HadGEM2-AO, MIROC5, MIROC-ESM and NorESM1-ME
7 GCMs in case of winter, namely, CESM1-CAM5, GFDL-ESM-2G, GFDL-ESM-2M, GISS-E2-H-1, MIROC5, MIROC-ESM-CHEM and NorESM1-ME

13.6 Future Rainfall Projection from Selected GCMs

As all the selected models in different seasons do not provide simulation of all available RCPs, so a multi-model ensemble is proposed to construct the future climate change scenarios. The multi-model ensemble is prepared using simulations from the following GCMs:

For annual rainfall, CCSM4, CESM1-CAM5, MIROC5, NorESM1-M and NorESM1-ME GCMs
For monsoon rainfall, bcc-csm1-1, CCSM4, GFDL-ESM 2G, MIROC5, NorESM1-M and NorESM1-ME
For pre-monsoon rainfall, CESM1-CAM5, CSIRO-Mk3-6-0, FIO-ESM, GFDL-ESM 2M, GISS-E2-H1, GISS-E2-R1, GISS-E2-R2, HadGEM2-AO, IPSL-CM5A-LR, MIROC5, MIROC-ESM-CHEM, MIROC-ESM and NorESM1-ME
For post-monsoon rainfall, FIO-ESM, GFDL-CM3, GFDL-ESM 2G, GISS-E2-R2, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM, MIROC-ESM-CHEM and NorESM1-M
For winter rainfall, CESM1-CAM5, GFDL-ESM 2G, GFDL-ESM-2M and NorESM1-ME

All these mentioned GCMs are in different seasons; the simulations for each model are commonly available under all the RCPs. Similar results can be seen over South Bengal which has not been displayed in the present chapter.

13.7 Ensemble Based Future Rainfall Change (in %)

The percentage of annual and seasonal rainfall with respect to the climatological base period of 1971–2000 is also calculated for different climatological periods for the 2020s, 2050s and 2080s, and results are shown in Tables 13.4 and 13.5. The annual rainfall for RCP4.5, RCP6.0 and RCP8.5 has shown increasing trends for 2050 and 2080s, while a slightly decreasing trend is also noticed for RCP2.6 over North Bengal. The winter rainfall has shown 60–117% surplus in future for different RCP scenarios, whereas the post-monsoon has shown a 1–15% surplus of rainfall in future over North Bengal. Similarly, the annual rainfall over South Bengal has

Table 13.4 Percentage (%) change of rainfall during annual and monsoon season over North Bengal and South Bengal with respect to 1971–2000

	Annual				Monsoon			
Time period	RCP26	RCP45	RCP60	RCP85	RCP26	RCP45	RCP60	RCP85
North Bengal								
2001–2030	−6.0	−5.3	−4.0	−2.6	−18.9	−17.7	−17.5	−16.6
2031–2060	−5.1	−2.5	−1.3	−3.7	−19.1	−16.3	−16.7	−16.9
2061–2090	−2.5	2.0	−0.1	3.1	−17.3	−15.0	−15.1	−11.1
2091–2100	−1.7	2.1	5.5	10.1	−15.8	−15.0	−10.9	−3.7
2001–2100	−4.3	−1.5	−1.1	0.1	−18.2	−16.2	−15.9	−13.7
South Bengal								
2001–2030	−24.9	−23.5	−22.8	−24.0	−34.4	−33.0	−34.3	−34.1
2031–2060	−23.6	−23.8	−22.9	−23.7	−31.1	−30.9	−32.9	−32.2
2061–2090	−23.1	−19.4	−23.0	−17.8	−30.9	−29.8	−28.9	−25.2
2091–2100	−22.1	−17.0	−19.6	−15.9	−32.9	−28.1	−28.3	−22.9
2001–2100	−23.7	−21.7	−22.6	−21.3	−32.2	−30.9	−31.7	−29.7

Table 13.5 Percentage (%) change of rainfall during winter and pre-monsoon season over North Bengal and South Bengal with respect to 1971–2000

	Winter				Pre-monsoon			
Time period	RCP26	RCP45	RCP60	RCP85	RCP26	RCP45	RCP60	RCP85
North Bengal								
2001–2030	75.5	77.7	98.4	89.9	−30.2	−31.0	−32.8	−29.5
2031–2060	64.4	87.1	74.8	69.3	−26.8	−29.5	−31.1	−29.6
2061–2090	81.3	72.1	67.2	82.5	−28.0	−27.3	−31.5	−22.2
2091–2100	59.4	117.2	69.6	85.2	−28.9	−25.2	−28.7	−19.3
2001–2100	72.3	82.8	79.1	81.0	−28.4	−28.9	−31.5	−26.3
South Bengal								
2001–2030	−24.0	−26.6	−19.3	−16.8	−59.7	−57.9	−57.9	−59.9
2031–2060	−20.9	−22.2	−18.9	−22.6	−59.7	−61.3	−61.3	−57.5
2061–2090	−18.0	−24.2	−27.6	−27.3	−59.5	−54.1	−54.1	−52.8
2091–2100	−23.6	−19.5	−19.2	−23.7	−59.4	−51.2	−51.2	−51.4
2001–2100	−21.2	−23.8	−21.7	−22.4	−59.6	−57.1	−57.1	−56.2

shown decreasing trends by 16–25% under different RCP scenarios and different climatological as well as long-term period, while 3–24% surplus of rainfall is projected for different RCP scenarios in the post-monsoon over South Bengal.

13.8 Application of ORYZA2000: Validation and Impact Study

Potential as well as nitrogen- and water-limited production situations are considered for *Boro* season (2000–2001). The potential production (~10 t ha^{-1}) appears to be more than the highest reported value (~9 t ha^{-1}) in West Bengal conditions. Application of N_2 fertilizer under N_2-limited situation assures more yields (~8–9 t ha^{-1}) up to a limit of 140 kg ha^{-1}. Further increase of N_2 application has less impact on the production, indicating an optimized amount of nitrogen fertilizer as 120–140 kg ha^{-1}. On the other hand, in water-limited situation, predicted yield components are less (~7 t ha^{-1}) (Table 13.6) even with the application of optimized amount of N_2 fertilizer.

Verification study indicates that the model estimation is more than the observed values. Keeping the overestimating nature of the model in view, the model has further been used to test its performance in simulation potential yield under climate change scenarios. How the final yield and different yield components vary under different level of increasing/decreasing temperature are shown in Fig. 13.3.

Simulations have been carried out under both the current value of CO_2 concentration and double CO_2 concentration. Apart from the usual nature of overestimation by the model, the yield gets reduced with the increase in temperature and vice versa. The simulated yield is enhanced by about 10% in case of doubled CO_2 concentration and 1^{0}C temperature increase when compared with the yield at current CO_2 concentration. This is particularly important when a temperature increase of 0.5–2.0 °C has been estimated for the period 2010–2039 over the study area. Similar type of work using ORYZA2000 was carried out by Swain et al. (2007) using a new rice variety named Ranjit, where he obtained high yield of 5.52 Mg ha^{-1} compared to conventional yield of 4.36 Mg ha^{-1}. He also suggested the highest-grain yield will be achieved if the rice is planted on 15 July during the wet season. Another study of ORYZA2000 over Hyderabad by Sailaja et al. (2013) showed that the simulated dry matter weight and yield values are close to the observation. ORYZA1 and INFOCROP were extensively applied to investigate the yield changes under elevated CO_2 and temperature (Krishnan et al. 2007) over ten locations of eastern India. Both models showed a decreasing amount of yield by −7.20 and − 6.66%, respectively, at 1.8 °C of temperature rise with the 380 ppm of current CO_2,, while yield increased by 30.73% in ORYZA1 and 56.37% in INFOCROP rice when CO_2 increased to 700 ppm. The ORYZA2000 model was also applied to investigate the variation rice yield under different irrigated regions of Punjab by Arora (2006) and reported a good performance of the model in depicting the observed yields in terms of several yield parameters. Similarly, Yadav et al. (2011) used ORYZA2000 model

Table 13.6 Comparison between the observed and model simulation yields

	Grain yield (t ha^{-1}) of field experiment			Grain yield (t ha^{-1}) simulated by Model		
Year	N00	N120	N140	N00	N120	N140
1999–2000	2.1	3.5	4.1	4.6	8.6	8.9
2000–2001	3.9	5.4	7.0	4.8	8.9	9.0

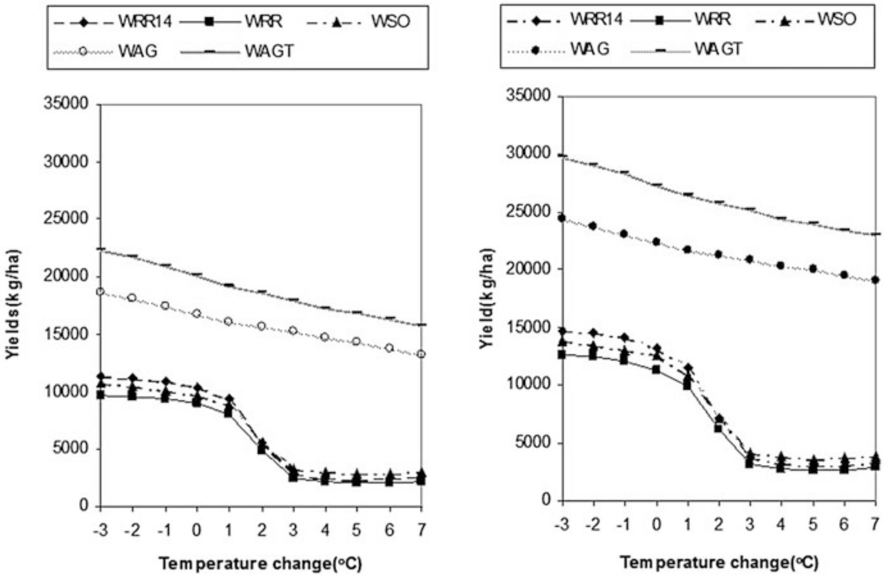

Fig. 13.3 Simulated yield components (kg ha^{-1}) for different changing temperature during the crop season 1999–2000 with 1 × CO_2 (left panel) and 2 × CO_2 (right panel)

to simulate the effects of water management on rice growth, yield and water productivity components over northwest India. Beyond India, ORYZA2000 model was also applied over Chile by Artacho et al. (2011) to explore potential yield and grain yield response to N fertilization under likely weather conditions in the major rice-producing area.

The main advantages of using the ORYZA2000 model are that it provides flexibility and transferability of the data and the programme code. It is expected to provide commercial output in terms of grain yield, fruits, root, biomass for fodder, etc. under varying weather conditions. Crop model can be apply extensively in the following management and operational purpose: (1) strategic planning in which crop models are run prior to planting, (2) practical evaluation in which crop models are run prior to crop growth duration and (3) forecasting crop yield in which models are run prior to during of the crop growth.

A study was conducted by Mukherjee et al. (2011) over Punjab region of India to compare the results for two simulation models, namely, WOFOST and ORYZA2000, using two rice varieties (PR 116 and PR 118) during 2006–2008 where ORYZA2000 model showed better performance compared to WOFOST in simulating the dry weight of leaves, dry weight of stem, aboveground biomass, leaf area index and grain yield. Another crop model named as Aqua crop model used by Singh et al. (2013) over the farm of Uttar Banga Krishi Viswavidyalaya at Majhian located in Dakshin Dinajpur District of West Bengal, India, indicated that model simulated wheat yield as 4.16tha^{-1}as compared to the actual yield of 4.10 t ha^{-1} in the year 2008–2009. Further study by Sarkar and Kar (2006) using DSSAT 3.5

model showed that the optimal rice and wheat yield are obtained under the application of 120 kg of nitrogen per hectare, whereas 80 kg of nitrogen per hectare for both rice and wheat is recommended from the literature. A recent study by Singh et al. (2016) using the CERES-Rice model from DSSAT 4.5 during *kharif* season for genetic coefficients of rice cultivars over four locations of India at Jorhat, Kalyani, Ranchi and Bhagalpur showed the potential rice yields are decreasing with the tune of 35.3, 1.9, 48.6 and 17.1 kg ha^{-1} day^{-1}, respectively, under delayed sowing.

13.9 Major Finding of Climate Change and Associated Impact

In general annual rainfall over North Bengal showed a decreasing trend of 134 mm/100 years at Jalpaiguri district to increasing trend of 420 mm/100 year over Cooch Behar district during 1901–2000 period, while all South Bengal districts showed increasing trends except Bardhaman and Nadia districts where a slight decreasing trend was observed during the last century. None of the CMIP5 model is able to reproduce mean seasonal cycles over North or South Bengal adequately, but multi-model ensemble using the better performing models does the same quite satisfactorily. Almost 50% of the total 42 models are able to simulate the increasing rainfall trends in annual, monsoon, winter and pre-monsoon seasons over North Bengal district, while the majority of the models indicate decreasing trends over South Bengal in annual and monsoon seasons. It is expected that annual rainfall over North Bengal will increase by 140–348 mm at the end the twenty-first century as per all RCPs, while winter rainfall is projected to decrease by 1–20 mm at the same time. At the end of the twenty-first century, annual rainfall over South Bengal districts is expected to increase by 29–167 mm. In terms of percentage change of rainfall with respect to the climatological base period of 1971–2000, the winter, pre-monsoon and monsoon rainfall will increase both for North and South Bengal as per all RCPs. Further, sensitivity study indicates that optimum use of N_2 is 140 kg ha^{-1} in this climatic condition with ample supply of water, which assures yield of about 8–9 t ha^{-1}. Verification analysis shows that the model overestimates the yield production. It is noticed that production of yield gets reduced with the increase of temperature and vice versa in the current as well as doubling CO_2 conditions. Increased CO_2 in the atmosphere indicates higher yield. Combined effect of CO_2 and temperature indicates less change of rice yield over the study area. It is concluded that the present-generation GCMs do not provide useful information for impact research or any policy-making issues at district or block level due to its courser scale resolution which is unable to capture the detail complexity of earth atmosphere system, but all these information can provide a realization about the past and future climate scenarios. These GCM simulations can be more reliably used for local scale decision-making after developing downscaled scenarios from the raw GCMs simulation. On the other hand, crop model still today cannot be used for operational purpose for day-to-day agricultural practice as it has its inherent biases and limitations to reproduce the crop phenology leading to different yield components adequately.

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Canopy Temperature-Based Water Stress Indices: Potential and Limitations

14

Manoj Kumar Nanda, Utpal Giri, and Nimai Bera

Abstract

Water stress in plant is associated with reduced availability of soil moisture under higher ambient temperature and wider vapour pressure deficit for a considerable period of time. Instruments like pressure chambers and porometers are being used to quantify crop water stress under field conditions, but their use is limited because of the numerous time-consuming measurements that must be made. The application of thermal indices involving canopy temperature for monitoring crop water stress and irrigation scheduling has been demonstrated by several researchers in the last five decades since the evolution of portable infrared thermometers in the 1960s. As the temperature of plant canopy is a manifestation of canopy energy balance, a water-stressed canopy is hotter than a well-watered one under the same environmental conditions. Infrared thermometer integrates the thermal radiation from all exposed surfaces in the field of view of the instrument that included the plant surface and exposed soil surfaces into a single measurement and converts it into temperature unit applying the principle of Stefan-Boltzmann law. However, different plant physiological as well as microclimatic factors like solar radiation, turbulence, air temperature and humidity must influence the canopy temperature at the time of observation. Hence, stomatal conductance and transpiration rates cannot be estimated by canopy temperature alone. In other words, canopy temperature alone is not enough to make estimates of plant water status. For this reason many researchers have attempted to normalize the canopy temperature to account for the influence of other variable

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microclimatic parameters like vapour pressure deficit, air temperature, wind speed, solar radiation, etc.

In the past few decades, a number of thermal indices have been applied to estimate crop water stress under field condition. The difference between canopy temperature and air temperature (canopy-air temperature difference, CATD) was the first and one of the most commonly used thermal indices to quantify crop water stress. The summation of CATD over some critical period in the crop's life cycle was termed as stress degree day (SDD). Similarly, the difference between canopy temperature of stressed and non-stressed plants has been used as an index called temperature stress day (TSD). The "canopy temperature variability" (CTV) takes into account the spatial variability of canopy temperature in crop field which was found to be higher in stressed plant than that of non-stressed plant. The temperature-time threshold (TTT) method assumes that the stress is not occurring in the crop until the canopy temperature reaches certain threshold value and calculates the amount of time that canopy temperature is greater than temperature threshold to quantify moisture stress. The crop water stress index (CWSI) further normalizes the canopy-air temperature difference with vapour pressure deficit of air. The calculation of CWSI quantifies the moisture stress of a plant as a comparison of its canopy temperature with that of a non-water-stressed plant and a maximum stressed plant with respect to their differences from the ambient air temperature at a given vapour pressure deficit. Conceptually, CWSI of a non-stressed and fully stressed (non-transpiring) plant is 0 and 1, respectively. The water deficit index (WDI) integrated the percent vegetation coverage and canopy temperature to compensate the effect of soil background that interferes in the remote measurement of canopy temperature through infrared thermometry. The "Biologically Identified Optimal Temperature Interactive Console (BIOTIC)" is an irrigation protocol that provides irrigation scheduling based upon measurements of canopy temperatures and the temperature optimum of the crop species of interest. But some critical issues like impact of rapid fluctuation in radiation and wind speed on crop water stress, crop to crop variability in stress tolerance and the requirement of stress at particular phenophases of some crops have not been duly focused. Thus the canopy temperature-based water stress indices have limited application in irrigation scheduling at field scale. However, with advancement of satellite-based optical and thermal remote sensing in recent years, there is a renewed interest in thermal indices for crop stress monitoring.

Keywords

Infrared thermometry · Canopy air temperature difference (CATD) · Stress degree day (SDD) · Canopy temperature variability (CTV) · Temperature stress day (TSD) · Crop water stress index (CWSI) · Water deficit index (WDI)

14.1 Introduction

Water stress is one of the most common types of plant stress and is often associated with reduced availability water from soil and during periods of high evaporative demand of atmosphere associated with higher ambient temperature and vapour pressure deficit. The negative effects of water stress on crop yield are both cosmopolitan and substantial, reducing yields in all cropping systems and regions worldwide. Generally, the production is adversely affected when a crop undergoes longer period of stress during its life cycle, although some plants may require a period of water stress to initiate reproductive development. An increase in plant water stress (decreasing plant water potential) occurs when an imbalance exists between the amount of water absorbed by the roots and the amount lost through transpiration. The degree of stress that develops is a function of the plant's environment. Popular methods that include pressure chamber and porometer that are being adopted to quantify crop moisture stress under field conditions have relied observations on a single plant or plant part. The pressure chamber measures leaf water potential of sample leaves removed from the growing plant (Correia et al. 2001). Porometer is frequently used for in situ measurement of stomatal conductance using portable chamber system (Turner 1991). Both the methods have potential to characterize crop water stress under field condition. However, these methods require numerous time-consuming measurements that limit their large-scale field application. However, for small plot research, these and similar methods provide useful information (Reginato 1983). Since the last few decades, the use of canopy temperature has received much attention for characterizing plant water stress with evolution of portable infrared thermometer (Idso 1982; Jackson et al. 1977, 1981).

14.2 Basic Principle

The plant leaves absorb a certain fraction of the incident radiation and partition this energy into three outgoing streams: reradiation, convective heat exchange with the air and evaporation of water or transpiration. In case of plant leaf, the heat conduction is too small to be considered significant, and for steady-state situations, the energy storage term is zero. Whenever water is evaporated from a leaf, the latent heat of evaporation is drawn from the leaf, cooling it down. Under water deficit conditions, stomata of leaves close in response to loss of turgor pressure (Kramer 1983), causing a lowering of transpiration rate. The dissipation of energy through latent heat is reduced leading to a positive energy balance. As the temperature of plant canopy is a manifestation of canopy energy balance, a water-stressed canopy is hotter than a well-watered one under the same environmental conditions. Testi et al. (2008) was of the view that the temperature of a canopy deviates from air temperature, in a way that is strictly dependent on the rate of transpiration under the same environmental conditions.

The energy budget of individual leaf in a plant canopy has been analysed in detail by Gates (1980). The empirical derivation of leaf temperature by Gates showed that for a leaf of characteristic dimension of 0.05 m and an internal resistance to water loss of 200 m s^{-1} at air temperature 30 °C, wind speed 1 m s^{-1} and relative humidity 50% the leaf temperature is 26 °C when the radiation absorbed by the leaf is 419 W m^{-2}. The leaf temperature is increased to 31.3 °C when the radiation absorption is 698 W m^{-2}, other conditions remaining similar. The non-transpiring leaf under similar conditions would have a temperature of 28.7 and 34.6 °C, respectively. Thus, the empirical analysis of Gates suggests that sunlit leaves would be warmer than air, whereas the lower-shaded leaves would be cooler than air, and transpiration was very important in the energy budget of plants.

14.3 Leaf Temperature Versus Canopy Temperature

The literature concerning leaf temperatures dates back at least to the early part of the eighteenth century. Jackson (1982) made a thorough review of the history of leaf temperature measurement and found that the leaf temperatures were higher than the air temperature in majority of the earlier reports. The earlier measurements involved clamping of sensors to the leaves or wrapping of un-detached leaves around the sensors. The major limitations in those measurements were that the leaves were not true representative of the whole canopy. The leaves were mostly near the top of plant under direct sunlight. As the quantity of absorbed radiation is the most influencing parameter in the energy budget of the leaf, the position of leaf in the plant stand (upper or lower leaf) is an important criterion in measurement of leaf temperature. Secondly, there was no standard location suggested for recording air temperature. Tanner (1963) was among the first researchers who studied canopy temperature with the help of infrared thermometry for monitoring plant water stress. Tanner was of the view that the temperature of individual leaf would fail to represent the status of the plant as a whole. A leaf with the surface normal to incident solar radiation will be at a substantially higher temperature than a leaf that has a large angle of incidence or one that is shaded. Thus, there is no single leaf temperature value that represents the plant to be useful for any given research problem. Nevertheless, the measurement of individual leaf temperature with contact thermometers is cumbersome and tedious. Furthermore, either attaching or inserting thermal sensors may affect the plant temperature that is to be measured. Hence, for studying response of crops to moisture stress, canopy temperature that represents the averaged condition of both sunlit and shaded leaves is a more acceptable parameter than that of leaf temperature.

14.4 Infrared Thermometry

Infrared thermometer integrates the thermal radiation from all exposed surfaces in the field of view (FOV) of the instrument that included the plant surface and exposed soil surfaces into a single measurement and converts it into temperature unit. Tanner

(1963) defined temperature measured with an infrared thermometer as the blackbody temperature that would produce the radiation entering the instrument from plant parts in the field of view. However, the target surface may include soil surface exposed through the layers of vegetation.

14.4.1 Principles of Infrared Thermometry

The principle of infrared thermometer is based on the Stefan-Boltzmann law which states that the total energy radiated per unit surface area of a blackbody across all wavelengths per unit time (also known as the black-body *radiant emittance*) is directly proportional to the fourth power of the blackbody's thermodynamic temperature T:

$$\text{For blackbody,} \quad R_{\text{blackbody}} = \sigma\, T^4 \tag{14.1}$$

$$\text{For greybody,} \quad R_{\text{greybody}} = \varepsilon\, \sigma\, T^4 \tag{14.2}$$

The constant of proportionality σ is called the Stefan-Boltzmann constant. The value of the constant is $5.67 \text{ x } 10^{-8}\ \text{W m}^{-2}\ \text{K}^{-4}$. A blackbody absorbs all radiation incident upon it, and its emissivity is also maximum. For the blackbody absorptivity, (a) = emissivity (ε) = 1. An object that does not absorb all the incident radiation and emits less energy than a blackbody is known as grey body. These grey bodies are characterized by their emissivity. The conventional IR thermometers work in wavelength range of 8–14 micrometre, the range in which most of the earth objects have high emissivity ($\varepsilon = 0.94$ to 0.98).

14.4.2 Errors Associated with IR Thermometry

There are different types of error associated with the IR thermometry. The first error is due to interference of atmospheric radiation. According to Monteith and Szeicz (1962), the total upward long-wave radiation (R_T) from a surface with emissivity (ε) may be written as the sum of thermal infrared radiation emitted by the object and the part of atmospheric radiation reflected by it.

$$R_T = \varepsilon\, \sigma\, T_s{}^4 + (1--\varepsilon)\, R_a = \varepsilon\, \sigma\, (T_s*)^4 \tag{14.3}$$

where T_s is the true temperature of the target surface, R_a is the atmospheric radiation received by the surface and T_s* is the apparent temperature of the surface assuming $\varepsilon = 1$.

The difference between the true temperature and apparent temperature has been derived by Monteith and Szeicz (1962) as

$$\mathrm{T_s} - \mathrm{T_s}^* \cong \frac{(\mathrm{R_T} - \mathrm{R_s})(1 - \epsilon)}{4\, \epsilon\, \sigma\, \mathrm{T_s}^3} \tag{14.4}$$

The apparent radiative temperature was about 0.2 °C less than the true temperature for vegetation and water surface and as high as 1.5 °C less than the true temperature for a bare soil. Another possible source of error is due to the radiative flux divergence or the loss of radiation in the path for the surface to the sensor. Monteith and Szeicz (1962) opined that the surface temperature of turf may be underestimated by about 1 °C during the day and overestimated by about 0.2 °C during night. For bare soil, the difference may reach −2 to –3 °C during the day. The third source of variation of apparent surface temperature might be due to direction of measurement with respect to sun's position and angle of measurement. Here, solar zenith, measurement zenith and azimuth angle influence the measurement. Monteith and Szeicz (1962) studied the influence of measurement geometry and found that in the direction sun (azimuth = 0°), the radiometer saw patches of grass completely shaded by vertical irregularities of the canopy, whereas at azimuth = 180°, all visible leaves were fully illuminated and therefore relatively warm as the sunlit part of the canopy is expected to be warmer than the shaded part. The temperature of the surface also decreased at solar zenith >70°, showing that the grass blades were cooler at their tips than deeper in the cover.

Kimes et al. (1980) opined that the thermal infrared sensor response to emissions from vegetation canopies may deviate significantly from that expected for a Lambertian surface (ideal diffusion surface). They obtained a difference of as great as 13 °C, when going from a viewing zenith angle of 0° to one of 80° for wheat canopy of leaf area index 1.5. The measured difference at different measurement zenith angle was function of vegetation canopy geometry and the vertical temperature distribution of the canopy components.

The errors associated with IR thermometry are appeared to be highly variable with respect to time of measurement (solar angle), measurement geometry (angle, direction and distance of measurement) and field of view (FOV). Kirkham (2005) opined that the overall error generally varied from 0.5 to 1.5 °C. By viewing the target obliquely, one would ensure that maximum amount of vegetation remains within the FOV of the IR sensor. Furthermore, the influence of the sun's angle that would affect the target temperature may be minimized by taking readings from different directions. Jackson et al. (1981) took eight measurements four facing the east and four facing the west between 1340 and 1400 local time at an angle of 30° to represent the canopy temperature of wheat. Kirkham (2005) also preferred the same viewing angle, and they held the thermometer 1.2 m away from the crop (corn) canopy.

14.5 Application of Infrared Thermometry in Stress Monitoring

The energy budget of plant leaf involves three modes of heat transfer, i.e. by radiation, convection and transpiration. Aston and Van Bavel (1972) used infrared thermometry to record an increase in canopy temperature as a result of increased short-wave and long-wave radiant loads on leaf arrays. They compared temperature increase of different surfaces and reported that the surface temperature increased by 2.5, 0.5 and 2.0 °C in dry blotting paper, wet blotting paper and leaves of the southern pea (*Vigna sinensis*), respectively. Such increase in temperature of artificial and real leaves has also been predicted by the leaf energy balance-soil water depletion model with an accuracy of 1 and 5% for the artificial and real leaves, respectively. Gates (1980) gave a detailed account of energy budget of leaf and derived that the leaf temperature is influenced by cooling produced by the evaporation of liquid water to water vapour in the mesophyll and its diffusion through the stomata and across the boundary layer to the free air beyond the leaf. Thus, the canopy temperature that represents the average condition of all the leaves of the plant would indicate the transpiration status of the plant as a whole.

Complications arise while interpreting canopy temperature recorded from field measurement because of plant physiological as well as microclimatic factors like radiation, turbulence, air temperature and humidity that influence the canopy temperature at any particular time of observation in crop field. Thus, the stomatal conductance and transpiration rate that represent plant water status cannot be estimated by measuring the canopy temperature alone. Hence, many researchers attempted to normalize leaf and canopy temperature to account for the influence of the environmental condition during the period of measurement.

14.5.1 Canopy-Air Temperature Difference (CATD) and Stress Degree Day (SDD)

One of the most widely used parameters for normalization of environmental factors in canopy temperature-based stress monitoring approach is air temperature. Erhler (1973) was among the first few researchers who described the relation between leaf-air temperature difference and plant water stress. He used fine wire thermocouples imbedded in cotton leaves to measure leaf temperature on well-watered plants and concluded that within an irrigation cycle, main long-term changes in cotton (*Gossypium*) are progressive leaf dehydration and consequent stomatal closure. During this drying period, if the leaf continues to absorb the same amount of energy throughout the cycle, it will heat up gradually. Consequently, a long-term measurement of leaf temperature (T_L) is an indirect guide to stomatal aperture and might serve as an indicator of the need for irrigation. A simultaneous measurement of air temperature (T_A) would help computing leaf-air temperature differences ($\Delta T = T_L - T_A$). These differences could be related to soil water depletion. But he also opined that other factors like air temperature, vapour pressure, wind speed, radiation and leaf resistance would be intimately related to transpiration and stomatal aperture and thus could regulate leaf temperature (T_L). It was evident from the study of Linacre (1967) that the leaf and air temperature are highly correlated. He suggested that the plants had an optimum temperature for growth. When the air temperature falls below the optimum temperature, the plant canopy will become warmer than air. If the air temperature is above the optimum value, the plant canopy will be cooler than air. Several authors have referred it as "equality temperature" or "crossover temperature". Blad and Rosenberg (1976) observed that the crossover temperature varies widely under advective conditions in case of alfalfa and corn. The effects of environmental factors on T_L must be determined or held constant before T_L or ΔT data can be used for irrigation scheduling.

Quantification of plant stress through infrared thermometry was first demonstrated by Idso et al. (1977) and Jackson et al. (1977). They proposed that the difference between the temperature of a plant canopy and the temperature of the surrounding air ($T_C - T_A$) might be an indicator of the water status of wheat, since water stress induces partial closure of stomata and reduces transpiration. This allows sunlit leaves to warm above ambient air temperature as it absorbs energy from the sun. They quantified the crop water stress in terms of stress degree day (SDD) which may be defined as the summation of canopy-air temperature difference ($T_C - T_A$) over some critical period in the life cycle of crop much like the concept of growing degree day (GDD).

$$\mathrm{SDD} = \sum\nolimits_{n=i}^{N} (\mathrm{T_c} - \mathrm{T_c})_{\mathrm{i}} \tag{14.5}$$

where "*i*" to "*N*" is the period under study. The $T_C - T_A$ should be recorded during mid-afternoon (about 2 p.m.), and the air temperature was defined as the temperature measured at 150 cm above the soil.

Idso et al. (1977, 1978) applied the concept of SDD to yield prediction. They have considered the period between the appearance of heads and awns to the end of plant growth as the critical period for SDD summation for grain crop like wheat, while for a forage crop such as alfalfa, the dry matter production per unit leaf area was a linear function of SDD summed over the entire period of vegetative growth.

Jackson et al. (1977) applied the concept of SDD to irrigation scheduling and provided the framework for possible automation of irrigation scheduling applying the concept of SDD over larger areas by using airborne thermal scanner measurements.

Reginato et al. (1978) successfully applied the concept of stress degree day to alfalfa, for predicting its forage yield as well as grain yield. Walker and Hatfield (1979) obtained an inverse relationship between SDD and final yield of beans. Helyes et al. (2006) also observed that the accumulated SDD during flowering season had inverse relationship with the yield of snap bean. They opined that each 1 degree higher SDD might cause 90–130 kg ha^{-1} yield loss. All these studies showed that the SDD model illustrated the effect of moisture stress on eventual yield of crop.

Idso et al. (1981) presented $T_C - T_A$ and vapour pressure deficit (VPD) data for several crops and showed that the relationship between $T_C - T_A$ and VPD, for well-watered crops under clear-sky conditions, was linear. Diaz et al. (1983) noted that evapotranspiration was inversely and linearly related to the cumulative SDD values for a variety of crops grown under water-stressed conditions. Canopy to air temperature difference is also correlated to soil moisture content and stem water potential of peach orchards (Wang and Gartung 2010).

14.5.2 Temperature Stress Day (TSD)

The difference between canopy temperature of stressed and non-stressed plants has also been used as an index to quantify moisture stress. The earlier studies of Tanner (1963) revealed a possible maximum temperature difference of 3 °C between irrigated and unirrigated potatoes (*Solanum tuberosum* L.) due to stomatal closure. Gardner et al. (1981a) suggested that a relative measure of plant water status can be obtained from the temperature difference between a well-watered plot and a stressed plot. They referred this temperature difference to as “temperature stress day” (TSD). Irrigations could be initiated when the stress plot reached a predetermined temperature above the well-watered crop. They found parabolic curve between difference in leaf water potential ($\Delta\psi$) and difference in canopy temperature between stressed and non-stressed plant (TSD) of grain sorghum. During initial phases of moisture stress, the transpiration is reduced leading to increase in canopy temperature and thereby increase in TSD up to a value of about 4 °C. Beyond that point, transpiration from the stressed plants is restricted sufficiently to cause a slight increase in the leaf water potential (ψ), but at the same time, TSD continued to increase because transpiration was restricted and more of the absorbed radiation caused heating of the plant. However, the stress was not always indicated in sorghum whenever the TSD was greater than 0, since the TSD of non-stressed crop varied about mean 0 and standard deviation of 0.3. Clawson and Blad (1982) used TSD values of 1.0–3.0 to initiate irrigation of corn. Gardner et al. (1981b) also correlated corn grain yields with TSD of plants grown under several irrigation regimes and successfully used daily midday TSD values during the pollination and grain-filling stages to predict grain yield with an accuracy of ±10%.

The appealing simplicity of the TSD was that it only required simultaneous measurement of canopy temperatures of a stressed and a well-watered field of same crop and soil type. No other measurements of other atmospheric or plant parameters were required to calculate TSD. However, Clawson et al. (1989) suggested that the TSD is not an environmentally independent index, it has strong dependency with the vapour pressure deficit of air, and thus it cannot be universally applied.

14.5.3 Canopy Temperature Variability (CTV)

Studies on canopy temperature have revealed that the spatial variability of canopy temperature in water-stressed crop was higher than that of non-stressed crop (Gardner et al. 1981b; Clawson and Blad 1982; Nielsen and Gardner 1987). This formed the basis of the "canopy temperature variability" (CTV) approach as a tool for determining crop water stress. However, the CTV approach was originally suggested by Aston and Van Bavel (1972). They found that the standard deviations of the canopy temperature were 0.3 °C for well-watered corn plots, while it was about 4.2 °C for water-stressed plots. The large variation in canopy temperature as a result of changing environmental factors (e.g. air temperature and radiation) suggested the use of in-field temperature variations due to differential drying of non-homogeneous soil as an indicator of plant water status.

Gonzalez-Dugo et al. (2006) made a detailed study on applicability of CTV concept to different levels of moisture stress and observed that at low moisture stress CTV in field was relatively small, whereas at moderate stress level, CTV was highly sensitive to water stress. However, at high stress level, assessment of moisture stress from CTV was poor and not recommendable. The major limitation of CTV concept is that the degree of uniformity of the root zone water availability of the field might differ from one another. This makes the application of threshold value (of CTV) or its empirical relationship with other stress indices difficult.

14.5.4 Time-Temperature Threshold (TTT)

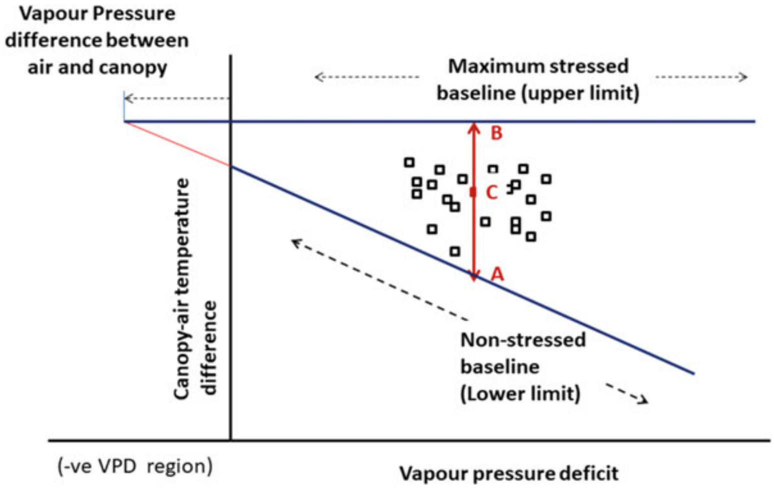
The TTT method assumes that stress is not occurring in the crop until it reaches the temperature threshold or T_{critical} and calculates the amount of time that canopy temperature (T_c) is greater than T_{critical}. Upchurch et al. (1996) received US patent no. 5,539,637 for an irrigation management system that was based on this optimal leaf temperature for enzyme activity and a climate-dependant time threshold. They termed it as "temperature-time threshold" (TTT) method of irrigation scheduling. In this approach, every minute the canopy temperature exceeds, the threshold temperature is added up to get cumulative value of TTT. An irrigation of a fixed depth is scheduled when the TTT exceeds the time threshold at the end of the day. The TTT approach can be mathematically expressed as

$$\mathrm{TTT} = \sum\nolimits_{h=0}^{24} \mathrm{h}, \quad \text{when } \mathrm{T_c} > \mathrm{T_{critical}} \tag{14.6}$$

The TTT approach has been successfully applied as a precision irrigation scheduling tool. The "Biologically Identified Optimal Temperature Interactive Console (BIOTIC)" is an irrigation protocol that provides irrigation scheduling based upon measurements of canopy temperatures and the temperature optimum of the crop species of interest. The BIOTIC protocol has been demonstrated to be an effective irrigation scheduling method for several crop species in both semiarid and humid environments (Mahan et al. 2005). However, it requires real-time monitoring of canopy temperature and judicious selection of critical temperature which is expected to be crop, climate and growth specific. Wanjura et al. (1995) described three methods for the determination of time thresholds: (1) empirical method based on field testing of multiple time thresholds for irrigation and the selection of the threshold that optimized crop performance, (2) empirical analysis of historical crop canopy temperatures for a crop grown under well-watered conditions and (3) theoretical determination of canopy temperatures of well-watered crop from energy balance analysis.

14.5.5 Crop Water Stress Index (CWSI)

The canopy temperature-based variables, namely, CATD (or SDD), CTV or TSD, as discussed earlier are aimed at normalizing canopy temperature with the air temperature. However, the evapotranspirative demand that determines the water stress in crop plant to a considerable extent is regulated by vapour pressure deficit of ambient air. The crop water stress index (CWSI) is a promising tool that further normalizes CATD with vapour pressure deficit (VPD) to quantify crop water stress (Jackson et al. 1981; Idso et al. 1981; Idso 1982; Jackson 1982). The calculation of CWSI is based on two baselines: the non-water-stressed baseline represented by a fully watered crop and the maximum stressed baseline, which corresponds to a non-transpiring crop where the stomata are assumed to be fully closed. The crop water stress index (CWSI) is conceptualized as the ratio of the distance of an actual T_c–T_a data point above the non-stressed baseline to the distance from the baseline to the upper limit, at a given VPD. Thus, a non-stressed plant had a CWSI value equals to 0, while that of a fully stressed non-transpiring crop had a CWSI value of 1.0.



According to Idso's definition (Idso et al. 1981), the CWSI can be expressed as

$$\mathrm{CWSI} = \frac{(\mathrm{T_c} - \mathrm{T_a}) - \mathrm{D_2}}{\mathrm{D_1} - \mathrm{D_2}} \tag{14.7}$$

where D_1 is the maximum value of canopy and air temperature difference for a fully stressed crop (the maximum stressed baseline), D_2 the lower limit canopy and air temperature difference for a well-watered crop (the non-water-stressed baseline), T_c the measured canopy surface temperature (°C) and T_a the air temperature (°C).

There are two popular approaches to define non-water-stressed baselines for determination of CWSI. One is the empirical approach given by Idso et al. (1981), in which the empirical relationship between the canopy-air temperature differences ($T_c - T_a$) and the vapour pressure deficit (VPD) is established from field measurements under different environmental conditions for a well-watered crop. The other approach by Jackson (1982) is based on the theoretically derived relationship between $T_c - T_a$ and VPD following one-layer canopy energy balance model.

14.5.5.1 Empirical Approach

Following Idso's approach, the empirical formula for non-water-stressed baseline is represented as

$$\mathrm{D_2} = \mathrm{A} + \mathrm{B.VPD} \tag{14.8}$$

where VPD is the air vapour pressure deficit (in Pa), *A* is the intercept and *B* is the slope of the linear regression equation of the lower limit canopy and air temperature difference and the vapour pressure deficit. Idso (1982) has given the regression coefficients of non-water-stressed baselines for 26 different plant species for clear-sky conditions and for 6 of these plants, including one aquatic species he had also given the regression coefficients under cloudy or shaded conditions.

The water-stressed baseline (D1) is a line plotted parallel to the x-axis with the assumption that the CATD remains unaltered by the changes in VPD under maximum possible stress when the transpiration is completely stopped. It has been observed from VPD vs CATD regression line given by several researchers for different crops that the canopy temperature is equal to the atmospheric temperature when the atmosphere is completely saturated (i.e. VPD = 0) as implied by positive value of the intercepts in the regression lines. This prompted Idso et al. (1981) to assume that even under completely saturated atmospheric condition, a positive vapour pressure gradient will exist between the foliage and the air, and thus, the transpiration from the plant canopy will not be fully suppressed. They have suggested extrapolating the VPD-CATD regression line beyond the atmospheric saturation level into the negative VPD zone until it reaches the point where atmospheric vapour pressure is equal to the canopy vapour pressure. The CATD at that point is referred to as the water-stressed baseline.

14.5.5.2 Theoretical Approach

The computation of CWSI according to Jackson et al. (1981) is based on theoretically derived relationship between Tc − Ta and VPD based on the one-layer canopy energy balance model. Jackson's derivation of CWSI is explained here for detailed understanding.

The energy balance of a crop canopy is explained according to Monteith (1973) as

$$\mathrm{Rn} = \mathrm{G} + \mathrm{H} + \lambda E \tag{14.9}$$

where Rn = net radiation, G = ground heat flux, H = sensible heat flux and E = latent heat flux (all expressed in W m^{-2}).

The storage energy is neglected in the present derivation. The flux components H and E can be expressed in simple forms as

$$\mathrm{H} = \rho \mathrm{C_p} \frac{\mathrm{T_c} - \mathrm{T_a}}{\mathrm{r_a}} \tag{14.10}$$

$$\lambda E = \frac{\rho C_p}{\gamma} \frac{e_c^* - e_a}{(r_a + r_c)} \tag{14.11}$$

where ρ = air density (kg m^{-3}), $\mathrm{C_p}$ = heat capacity of air (J kg^{-1} $^\circ\mathrm{C}^{-1}$), $\mathrm{T_C}$ = surface (canopy) temperature (°C), $\mathrm{T_a}$ = air temperature (°C), $\mathrm{e_c}^*$ = saturated vapour pressure (Pa) at $\mathrm{T_c}$, $\mathrm{e_a}$ = vapour pressure (Pa) of air, $\mathrm{r_a}$ = aerodynamic resistance (s m^{-1}) and $\mathrm{r_c}$ = canopy resistance (s m^{-1}) to vapour transport. Combining Eqs. (14.9), (14.10) and (14.11), assuming G is negligible and defining Δ = slope of saturation vapour pressure temperature relation $(\mathrm{e_c}^* - \mathrm{e_a}^*)/(\mathrm{T_c} - \mathrm{T_a})$ expressed in Pa $^\mathrm{o}\mathrm{C}^{-1}$, the canopy-air temperature difference can be written as

$$\mathrm{T_c} - \mathrm{T_a} = \frac{r_a Rn}{\rho C_P} \cdot \frac{\gamma(1 + r_c/r_a)}{\Delta + \gamma(1 + r_c/r_a)} - \frac{VPD}{\Delta + \gamma(1 + r_c/r_a)} \tag{14.12}$$

where VPD = vapour pressure deficit of air = saturated vapour pressure ($e_a{}^*$) − actual vapour pressure (e_a) of air.

Equation 14.12 relates $\mathrm{T_c} - \mathrm{T_a}$ to the vapour pressure deficit of air. The upper limit of $\mathrm{T_c} - \mathrm{T_a}$ (water-stressed baseline) can be obtained from Eq. (14.4) by setting $\mathrm{r_c} \rightarrow \infty$ as

$$D_1 = \frac{r_a Rn}{\rho C_P}. \tag{14.13}$$

The lower limit of $\mathrm{T_c} - \mathrm{T_a}$ (non-stressed base line) may be defined from Eq. (14.12) by setting $r_c = r_{cp}$. The canopy resistance at potential evapotranspiration (r_{cp}) is probably not zero (van Bavel and Ehrler 1968). Thus the lower limit (non-stressed baseline) is defined as

$$D_2 = \frac{r_a R_n}{\rho . C_p} \cdot \frac{\gamma\left(1 - r_{cp}/r_a\right)}{\Delta + \gamma\left(1 - r_{cp}/r_a\right)} - \frac{VPD}{\Delta + \gamma\left(1 - r_{cp}/r_a\right)} \tag{14.14}$$

Equation 14.14 represents the linear relation between vapour pressure deficit of air ($e_a^* - e_a$) and canopy-air temperature difference ($T_c - T_a$) under certain values of r_{cp} and r_a. Since Δ appears in intercept and slope, both the terms are temperature dependent. Thus, the lower limit is temperature dependent.

For simplifying the derivation of CWSI, Jackson et al. (1981) used a measure of the ratio of actual to potential evapotranspiration (E/E_p) taking into consideration of the Penman-Monteith equation of potential evapotranspiration (E).

$$\lambda E = \frac{\Delta Rn + \rho C_p\left(e_a^* - e_a\right)/r_a}{\Delta + \gamma(1 + r_c/r_a)} \tag{14.15}$$

The ratio of actual and potential evapotranspiration, thus, can be written as

$$\frac{E}{E_p} = \frac{\Delta + \gamma\left(1 + r_{cp}/r_a\right)}{\Delta + \gamma(1 + r_c/r_a)} \tag{14.16}$$

where r_{cp} is canopy resistance at the rate of potential evapotranspiration. The value of E/E_p ratio is assumed to vary from 0 (no available water where $r_c \rightarrow \infty$) to 1 (ample available water where $r_c = r_{cp}$). Thus the CWSI is defined as

$$CWSI = 1 - \frac{E}{E_p} = \frac{\gamma(1 + r_c/r_a) - \gamma\left(1 + r_{cp}/r_a\right)}{\Delta + \gamma(1 + r_c/r_a)} \tag{14.17}$$

Now for calculation of *CWSI*, it is important to quantify the resistance terms r_a, r_c and r_{cp}. The r_a is calculated by the following Monteith (1973) equation when the wind speed is >2 ms^{-1}.

$$r_a = \left\{ \frac{\ln\left[(z - d)/z_0\right]/K\}^2}{u} \right. \tag{14.18}$$

When the winds peed is ≤2 ms^{-1}, r_a is calculated following Thom and Oliver (1977) wind function derived for the Penman's evaporation equation.

$$r_a = 4.72\left[\frac{\ln{(z - d)/z_0}]^2}{1 + 0.54u}\right. \tag{14.19}$$

where z is the reference height (2 m), d the displacement height (m), z_0 the roughness length (m), k the von Karman constant (0.41) and u the wind speed ($m\ s^{-1}$). The roughness length and zero plane displacement can be derived as functions of the crop height (h). A convenient value of d and z_0 may be assumed as 0.56 h and 0.13 h, respectively, following Legg and Long (1975).

Equation 14.9 requires the value of r_c/r_a which can be obtained by rearranging Eq. 14.4 as follows:

$$\frac{r_c}{r_a} = \frac{\gamma r_a Rn/(\rho C_P) - (T_c - T_a)(\Delta + \gamma) - VPD}{\gamma\,[(T_c - T_a) - r_a Rn/(\rho C_P)]} \tag{14.20}$$

The canopy resistance at potential evapotranspiration (r_{cp}) is approximated by Jackson et al. (1981) iteratively by adjusting r_{cp} until the CWSI value obtained near zero after a fresh irrigation. This was a one-time approximation.

Later on, a baseline was proposed by Alves and Pereira (2000), which evaluated the radiometric surface temperature of fully transpiring crop in Jackson's definition as a "surface wet bulb temperature" and thus avoided the use of the surface resistances of crop. They assumed that the infrared surface temperature of fully transpiring crops can be regarded as a surface wet bulb temperature (T_{sw}) expressed as follows:

$$T_{sw} = \frac{\gamma}{\Delta + \gamma} . \frac{r_a\,(R_n - G)}{\rho.C_p} + T_w \tag{14.21}$$

where T_w is the wet bulb air temperature (°C).

So, the non-water-stressed baseline can be expressed as

$$D_2 = \frac{\gamma}{\Delta + \gamma} . \frac{r_a\,(R_n - G)}{\rho.C_p} + T_w - T_a \tag{14.22}$$

Equation 14.22 can be written as

$$D_2 = \frac{\gamma}{\Delta + \gamma} . \frac{r_a\,(R_n - G)}{\rho.C_p} + \frac{VPD}{\Delta + \gamma} \tag{14.23}$$

Comparing Eq. 14.23 with Eq. 14.14, it can be found that the contribution of ground heat flux (G) is ignored in Jackson's approach and that in Alves' definition, the crop minimum surface resistance (r_{cp}) is set to zero.

14.5.5.3 Field Application of CWSI

The preliminary evaluation of CWSI based on field data of winter wheat (Jackson et al. 1981) showed that after each irrigation, the CWSI gradually increased with time roughly in parallel with the trend of extractable water used. They found that the CWSI did not reach its lowest value immediately after irrigation. Instead, it required 5–6 days for CWSI to reach minimum value implying that the stressed wheat required some time to recover. Again, at the senescence stage, the canopy temperature remained high even though the extractable water used were low.

Hatfield (1983) obtained extremely good fit while studying the relation of accumulated CWSI values with available water extracted by grain sorghum and concluded that canopy temperature can be correlated with soil-water availability in some circumstances without additional data such as spectral reflectance. Keener and Kircher (1983) studied the relationship of SDD, CWSI (empirical) and CWSI (theoretical) with yield and kernel number of maize and found that in the humid condition, the SDD index showed no relationship with yield, whereas the CWSI (theoretical) gave the best relation with both yield and kernel number.

However, Kelly (1989) found poor correlation of CWSI (theoretical) with the water use by turf grass in the lysimetric study, and he attributed the mismatch to the measurement constraint associated with smaller field of view of the IR thermometer, rapid fluctuation of environmental parameters like net radiation, air temperature, wind speed and VPD and the probable error in estimation of aerodynamic resistance.

Taghvaeian et al. (2012) applied the CWSI model to predict the moisture content of the thin layer of topsoil of irrigated maize and obtained strong relationship between them with a high coefficient of determination. The empirical CWSI approach was accurate in computing crop water use as the physically based and more computationally intense remotely sensed surface energy balance (RSEB) model implemented in this study.

Agam et al. (2013) compared the theoretical and empirical CWSI models in their study on olive tree. The empirical CWSI differentiated between the well-watered and the stressed trees and depicted the water status dynamics both during the drought and recovery periods and on a diurnal scale. In contrast, the theoretically derived CWSI failed to capture the dynamics on both time scales. They attributed the failure of theoretical CWSI to the misrepresentation of the aerodynamic resistance to sensible heat transport in olive.

Alderfasi and Nielsen (2001) demonstrated the application of CWSI (empirical) to irrigation scheduling of wheat. However, they found that the data from a single-day measurement might not be enough to determine non-water-stressed baselines and proposed that for wheat crop, a distinctly different baseline should be used for pre-head and for post-head growth stages.

Çolak et al. (2015) used CWSI for irrigation scheduling of eggplant and concluded that the eggplant should be irrigated at CWSI values between 0.18 and 0.20 for high and good quality yields. They also found significant linear relations between the yield and CWSI under different irrigation treatments.

Colak and Yazar (2017) applied the CWSI approach for irrigation scheduling of grape vine. They determined lower (non-stressed) and upper (stressed) baselines empirically from measurements of Tc, Ta and VPD values and calculated the CWSI for each irrigation treatment. They found significant linear relations between the grapevine yield and CWSI and concluded that grapevine should be irrigated at CWSI values between 0.20 for high- and good-quality yields.

14.5.5.4 Critical Issues in Application of CWSI Approach

The CWSI has been considered as a promising tool for the quantification of crop water stress (Jackson et al. 1981). However, there are some critical issues which must be addressed for successful application of CWSI model at field scale.

14.5.5.4.1 Measurement Complexity

Even though CWSI seems to be scientifically sound, the greatest limitation of its application by any of the approach is the concurrent measurement of air temperature and humidity (in Idso's approach) and additional parameters like wind speed, net radiation (in Jackson or Alves and Pereira approach) and then estimation of the baselines. The whole process is too complex to be applied at farmers' level.

14.5.5.4.2 The Resistance Terms

Jackson's approach requires aerodynamic and canopy resistance among other parameters. Précised estimation of canopy and aerodynamic resistance is difficult. The aerodynamic resistance is highly variable with time and space, and it depends on both wind speed and temperature profile, specifically in a thermally stratified layer. However, for practical purpose, such complexity has been avoided by Alves and Pereira in the modified form of Jackson's approach. Alves and Pereira (2000) have simplified Jackson's approach by assuming crop minimum surface resistance at potential evapotranspiration (r_{cp}) to be zero. Though this assumption seems to be an oversimplification, it helps to avoid the difficulty of estimating the critical parameter r_{cp}.

14.5.5.4.3 Definition of Baseline

Defining water-stressed and non-stressed baseline has been the most critical step in CWSI approach. Alves and Pereira (2000) were of the view that the Idso's baseline has to be determined experimentally, which precludes its applicability to different climatic conditions (other places, other times of the day). Several other workers have recommended that the non-stressed baseline of Idso's empirical approach is specific to crop, growth stage and climate (Alderfasi and Nielsen 2001; DeJonge et al. 2015).

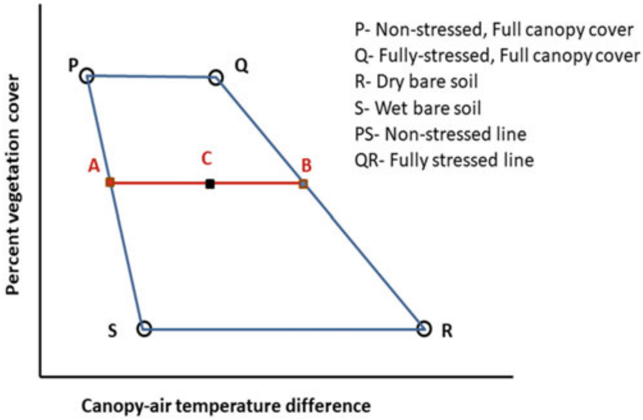
Jackson's approach on the other hand is based on the theoretical relationship among the microclimatic parameters in respect of vapour diffusion at stomata level to transport of vapour in the lower boundary layer, both driven by energy balance and aerodynamic process as well as supply of soil moisture. There are set of parameters either to be measured or estimated or assumed to be constant. Yuan et al. (2004) compared the CWSI computed by Idso's approach with that of Jackson's approach and Alves' approach in their study on winter wheat in China. They are of the view that the empirical CWSI based on Idso's approach may not be always applicable for evaluating water stress of winter wheat as the CWSI showed large fluctuations and frequently recorded the value outside the range of 0.0–1.0. The Jackson's approach was shown to be more reasonable to quantify the crop water stress, while the Alves' approach would be more practical for determining CWSI because it did not require the estimation of the crop canopy surface resistance. Again, because CWSI values based on Jackson's definition were different from that of Alves' definition for the same water stress degree, appropriate threshold CWSI should be considered when they are used for irrigation scheduling.

14.5.5.4.4 Vegetation Fraction and Exposure of Soil Surface

The system of canopy temperature measurement is applied for the crop canopy that fully covered the background soil. However, the soil surface often dries up after few days of irrigation and offers a warmer surface though the sub-surface has abundant moisture to support evapotranspiration at a rate reasonably close to potential evapotranspiration. Thus, the soil background included in surface temperature measurement can lead to false indication of water stress, especially when the surface soil is dried up.

14.5.6 Water Deficit Index (WDI)

To overcome the limitation of CWSI under fractional canopy coverage, Moran et al. (1994) conceptualized water deficit index (WDI) that uses surface-air temperature difference and vegetation index to estimate relative water status of a field. They assumed a trapezoid by taking four vertices as well-watered full canopy-covered crop, wet bare soil, non-transpiring fully covered crop (fully stressed) and dry bare soil in a scattered plot of percentage canopy cover versus surface-air temperature difference. The WDI was computed similar that of CWSI as the ratio of the displacement of CATD of the target plot from fully stressed line to the difference between fully stressed and non-stressed line as demonstrated in the given diagram. The possible error due to exposure of soil background, whose temperature would be different from that of the plant surface, is overcome in WDI approach. The concept of water deficit index is illustrated in the figure.



The WDI concept is being widely used for satellite-based determination of crop water stress, where the vegetation cover is approximated by the remote sensing-based vegetation indices like normalized difference vegetation index (NDVI) or soil-adjusted vegetation index (SAVI) or surface albedo. Both canopy temperature (land surface temperature, LST) and air temperature can also be derived from thermal remote sensing (Moran et al. 1994; Petropoulos et al. 2009).

14.6 Conclusion

The application of thermal indices involving canopy temperature for monitoring crop water stress and irrigation scheduling has been demonstrated by several researchers in the last four decades since the evolution of portable infrared thermometers in the 1960s. The researchers have developed different scientific tools for normalizing the influence of other variable microclimatic parameters like vapour pressure deficit, air temperature, wind speed, solar radiation, etc. While the simple indices like stress degree day (SDD), temperature stress day (TSD), canopy temperature variability (CTV), etc. provide quick and non-destructive assessment of crop water stress, the crop water stress index (CWSI) has been demonstrated as a promising tool to give crop moisture stress with due consideration of energy balance and evaporative demand of the atmosphere. These indices have shown good correlation with crop yield. The integration of percent vegetation coverage and canopy temperature as demonstrated in water deficit index (WDI) compensates the effect of soil background that interferes in the remote measurement of canopy temperature through infrared thermometry. However, few issues like the requirement of stress at particular phenophases of some crops, crop to crop variability in stress tolerance and rapid fluctuation in radiation and wind speed have limited the large-scale application of these tools in irrigation scheduling. The thermal indices have wide scope of application as precision irrigation scheduling tools. With advancement of satellite-based optical and thermal remote sensing, the importance of thermal indices for stress monitoring has increased in recent years.

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Part IV

Stress Impacts on Agricultural Commodities: Few Case Studies

15 Shift in the Manifestations of Insect Pests Under Predicted Climatic Change Scenarios: Key Challenges and Adaptation Strategies

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and A. K. Dhawan

Abstract

Climate change is now a scientifically proved, well-established and globally accepted fact. The impacts of climate change have already been observed frequently at many places in the form of rise in atmospheric CO_2 levels, increased temperatures, changing hydrological cycles and frequent occurrence of extreme weather events. The biotic communities may respond to these changes in a variety of ways. The diversity and abundance of insect pests in agroecosystems are very likely to be affected negatively under abiotically stressful environment in changing climate. Vast majority of studies have documented these effects on inhabitant biota, e.g. shift in range of geographical distributions and abundance, changes in phenology and species interactions, etc. Majority of the studies dealing with the impact of climate change on crop-insect pest interactions revealed the predominance of negative impacts of climate change on crop yields over the positive impacts. This may affect seriously the agricultural production and the livelihood of farming communities. This situation is expected to be more pronounced in tropical and subtropical countries of the world where larger proportion of work force is directly depending on climate-sensitive sectors such as agriculture, livestock and forestry. This article highlights the major changes in manifestations of insect pests of agricultural crops and their damaging activities in the context of

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predicted climatic changes. Besides, discussions were also added on planning and development of adaptive strategies and robust technologies that will be effective in management of the new and emerging pest problems in agroecosystems of future.

Keywords
Abiotic and biotic stresses · Climate change · Climate resilience · Food security · Insect pests · Outbreaks · Sustainability

15.1 Introduction

15.1.1 The Challenge: Climate Change, Agroecosystem Functioning and Species Composition

The climate of planet Earth is changing at rates never before witnessed by its inhabitants. The climatological studies have revealed increase in global temperatures, changes in atmospheric gas composition, greater variability in precipitation and frequent occurrence of extreme weather events (IPCC 2007, 2013). According to fifth assessment report of Intergovernmental Panel on Climate Change, the mean surface temperature of the Earth system is predicted to rise by 2.7–4.7 °C by the end of the twenty-first century (IPCC 2013). Equally, CO_2 concentration in the atmosphere has increased dramatically from 280 ppm to 370 ppm during the past 100 years and is predicted to double in 2100 (IPCC 2014). The communities of biotic organisms are very likely to respond to these changes in a variety of ways. There exist vast majority of empirical studies documenting these effects on inhabitant biota, e.g. shift in range of geographical distributions and abundance (Parmesan and Yohe 2003; Kelly and Goulden 2008) and changes in phenology and interactions among species (Levine and Paige 2004; Roy et al. 2004; Adams et al. 2009).

The interactions between abiotic and biotic components govern the functioning and species compositions of agroecosystems. The major abiotic factors of concern are temperature, humidity, rainfall, soil factors, pollutants, etc., whereas crop plants, weeds, insect pests, pathogens, nematodes, etc., constitute the major biotic factors (Pedigo 2006; Odum and Barrett 2008). The abiotic factors, mainly the temperature and rainfall, modulate the effects of biotic stresses and are most harmful when occurring in combination (Mittler 2006; Fand et al. 2012), it can greatly influence crop growth and productivity to the extent of 80% (Oerke 2006). Climate change, an outcome of anthropogenic pressures on the environment and manifests by means of changes in hydrological cycles (Rowntree 1990; IPCC 2007, 2013) and temperature regimes (IPCC 2013), may alter the composition of agroecosystems resulting in shift of distributions and ranges of associated animal and plant species (Porter et al. 1991; Sutherst et al. 1991; NACCAP 2008). Assessment of many regional studies covering a wide range of crops revealed that the negative impacts of climate change on crop yields are predominant than positive impacts (IPCC 2014). Thus, agriculture being a highly climate-sensitive sector, climate change may have drastic consequences for agricultural productivity worldwide through amplification of the already serious challenges like frequent weather vagaries, increased intensity of biotic and abiotic stresses and changes on the geographic distributions of species (Fand et al. 2012).

15.1.2 Insect Pests in the Era of Climate Change

Insect pests of crop plants are the real candidates most affected by global climate change due to their poikilothermic nature and inability to adjust with the changing temperature conditions (Bale et al. 2002; Petzoldt and Seaman 2010). Besides, other factors that affect spatio-temporal abundance and distribution of insects are relative humidity, wind velocity, rainfall and associated dry spells, host plant availability and their nutritional status, etc. The crop plants under abiotic stresses such as increased temperature and drought may be more susceptible to damage by insect herbivores due to biochemical changes like decreased defence compounds and increased nitrogen: carbon ratios in their leaves that result in increased palatability to insects, particularly the phloem sap feeders (White 1984; Fand et al. 2012). In this context, it is highly expected that, major drivers of climate change, i.e. elevated CO_2, increased temperature and depleted soil moisture can impact population dynamics of insect pests that enhance crop losses, significantly (Caulifield and Bunce 1994; Petzoldt and Seaman 2010). Complex physiological effects exerted by an increase of temperature and CO_2 may affect profoundly the interactions between crop plants and insect pests (Hare 1992; Caulifield and Bunce 1994; Roth and Lindroth 1995; Petzoldt and Seaman 2010; Fand et al. 2012). It has been reported that, global climate warming may lead to expansion and/or shift of the geographic ranges of insect pests (Hill and Dymock 1989; Parry and Carter 1989; Elphinstone and Toth 2008; Kroschel et al. 2014; Fand et al. 2014a, b), increased abundance of tropical insect species (Cannon 1998; Patterson et al. 1999; Bale et al. 2002; Diffenbaugh et al. 2008), decrease in the relative proportion of temperature-sensitive insect population (Petzoldt and Seaman 2010; Sharma et al. 2005, 2010), more incidence of insect transmitted plant diseases through range expansion and rapid reproduction of insect vectors (Petzoldt and Seaman 2010), increased overwintering survival due to milder winters (Harrington et al. 2001; Bale et al. 2002; Bale and Hayward 2010), increased number of generations due to accelerated growth rates and shorter generation times (Yamamura and Kiritani 1998; Bale et al. 2002; Ward and Masters 2007; Kroschel et al. 2014; Fand et al. 2014a, 2014b, 2015), increased risk of introducing invasive alien species (Sutherst et al. 1991; Mooney and Hobbs 2000; Ward and Masters 2007), breakdown of host resistance to insect pests due to increased environmental stress and reduced vigour (Rhoades 1985; Kaiser 1996; Hilder and Boulter 1999; Kranti et al. 2005; Sharma et al. 2005) and disruption of synchrony between life cycles of insect pests and their natural enemies leading to failure of biological control (Bale et al. 2002; Gutierrez et al. 2008). Thus, with changing climate it is expected that the growers of crops have to face new and intense pest problems in the years to come.

Insect pest damage is one of the limiting factors to agricultural productivity, which accounts for worldwide average yield losses to the tune of 16–18% (Oerke 2006). Abiotic environmental changes are predicted to benefit herbivorous insects resulting into increase in the number and frequency of outbreaks (Porter et al. 1991; Bale et al. 2002; Ward and Masters 2007). The spread, dispersal and invasion of agricultural pests will also be prone under climate change, and it may lead to high levels of damage to crops resulting in significant yield losses if pest management strategies to cope with the changing situations are not well in place (Estay et al. 2009; Berzitis et al. 2014; Fand et al. 2015). This may have serious consequences for agriculturally dependent economies. This chapter presents a detailed account of climate change associated challenges for crop insect pest management and also suggests the strategies for adaptation to cope with changing situations.

15.2 Predicted Shift in Pest Manifestations Under Potential Climatic Changes

15.2.1 Shift in the Range of Geographic Distribution and Abundance

The spatio-temporal distribution and abundance of organisms in nature are determined mainly by the climatic conditions of the region. Thus, every species has its unique climate envelope essential for its growth, survival and reproduction, which ultimately determines its abundance and distribution (Odum and Barrett 2008; Fand et al. 2012). Therefore, it is obvious that the future distribution and abundance of the species will be largely governed by the key elements of potential climate change, i.e. changing temperature and rainfall patterns, occurrences of frequent droughts, reduced stored soil moisture and certain extreme weather events like cyclones, storms, hailstorms, etc. (NACCAP 2008; IPCC 2013). From this it can be concluded that, the climate change may alter the future suitability of geographical areas for distribution, survival and reproduction of species due to inhospitable climatic conditions. In due course of time, the climate susceptible species may either perish locally or expand their geographical ranges to new suitable areas (Petzoldt and Seaman 2010; Fand et al. 2012).

In addition to the climatic suitability, availability of suitable hosts is the key factor determining seasonal population abundance of insect pests in agricultural ecosystems. Due to shift in cultivation areas of crop plants to higher altitudes with climatic change, the associated insect fauna are likely to be affected significantly (Thomas et al. 2004). Many studies have shown that due to rise in temperature, the insect pests may extend their geographic range from tropics and subtropics to temperate regions along with shifts in cultivation areas of their food plants (Rosenzweig et al. 2001; Parmesan and Yohe 2003; Logan et al. 2003; Elphinstone and Toth 2008; Sharma et al. 2005, 2010), resulting in increased abundance and sudden outbreak of tropical insect species at higher altitudes (Cannon 1998;

Patterson et al. 1999; Bale et al. 2002; Diffenbaugh et al. 2008; Kannan and James 2009). On the other hand, temperature increase in temperate region may affect negatively the temperature-sensitive insect population (Petzoldt and Seaman 2010; Sharma et al. 2005, 2010). Fand et al. (2014a, b, 2015) carried out a detailed analysis of climate change impact on the future distribution and damage potential of *P. solenopsis* affecting cotton in India. The authors reported that the suitability for occurrence of *P. solenopsis* will increase in geographical areas at higher latitudes with marginal increase of its abundance and damage potential. There will be a progressive increase in the abundance and damage related to *P. solenopsis* in the present distribution range, with a significant increase in tropical and subtropical cropping regions (Fig. 15.1).

15.2.2 Shift in Number of Generations per Season or Year

Due to lack of precise thermoregulation mechanisms, the developmental rate in insects is highly contingent upon external temperature conditions. It has experimentally been proved by many studies that the rate of development in insects increases with increase in temperature within the favourable limits, thus leading to reduced developmental times for completing their life cycles (Kroschel et al. 2013; Prasad et al. 2012; Fand et al. 2014a; Khadioli et al. 2014; Fand et al. 2015).

The rates of development, reproduction and survival in insects are expected to be faster under warmer temperatures of future. Thus, the time required for completion of life cycle by any given insect species will be shorter under potential climate warming conditions, enabling it to complete more number of generations than it could do so presently. Ultimately it will result in more crop damage than usually occurs (Yamamura and Kiritani 1998; Bale et al. 2002). Recent studies on temperature-dependent insect phenologies of potato tuber moth *Phthorimaea operculella* (Kroschel et al. 2013), cotton mealybug *Phenacoccus solenopsis* (Fand et al. 2014b), maize stem borer *Chilo partellus* (Khadioli et al. 2014) and common cutworm *Spodoptera litura* (Fand et al. 2015) have predicted that these pests may complete additional (with reference in the year 2000) 1–3 generations per year by the year 2050 (Fig. 15.2). The increased number of generations per year or season has serious implications for increased invasiveness of insect pests of economically important agri-horticultural crops under predicted climate warming (Fand and Suroshe 2015).

15.2.3 Shift in Manifestation of Diapause

Insects have limited ability of homeostasis with external temperature changes because of their poikilothermic nature. Hence they have developed a range of strategies for survival under stressful environments such as behavioural avoidance through migration and physiological adaptations like diapause (Bale and Hayward 2010; Fand et al. 2012). During diapause developmental activities remain

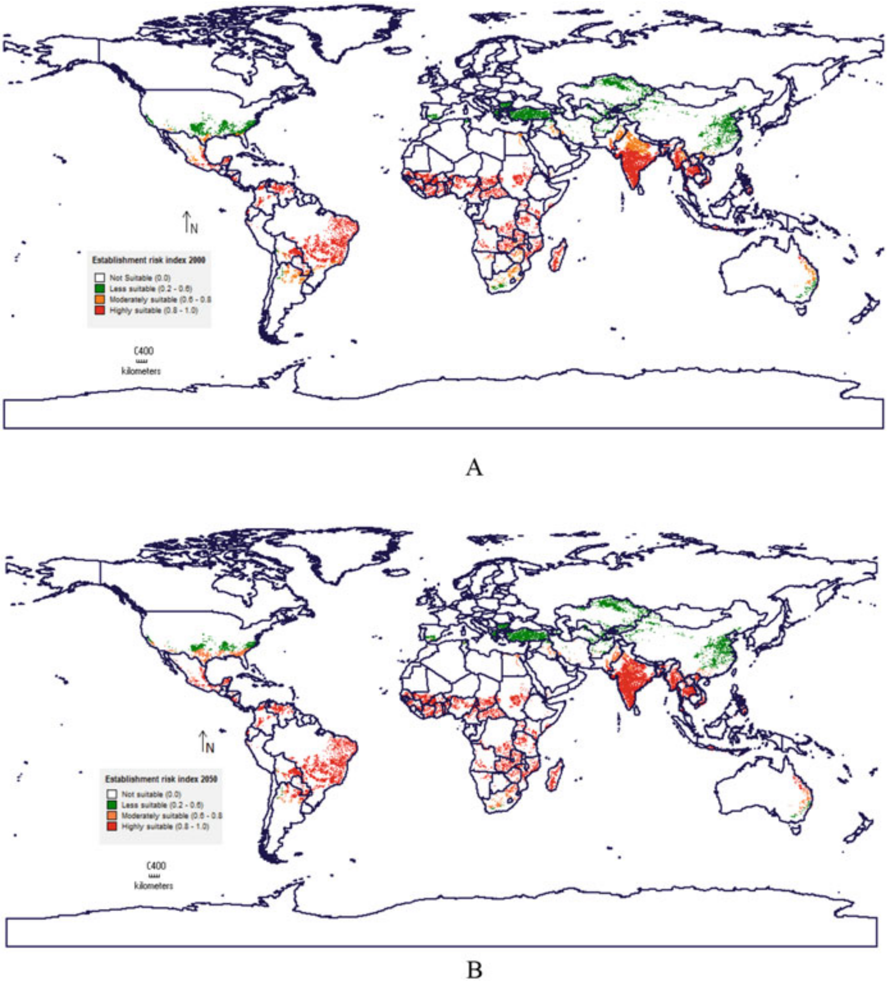

Fig. 15.1 Change in establishment and future distribution of *Phenacoccus solenopsis* in cotton production areas worldwide, based on establishment risk index (ERI) for current (**a**) and future (**b**) climatic conditions. (For more details, please see Fand et al. 2014b)

suspended, and the manifestation of diapause is primarily governed by temperature, humidity and photoperiod. Diapause plays important role in seasonal regulation of insect life cycles which enables the insects to survive under harsh environments. In insects, the diapause is of two main types: aestivation and hibernation to sustain life under high and low temperature extremes, respectively (Chapman 1998).

Global warming is occurring considerably in winter than in summer and is greatest at high latitudes, according to most of the climatological studies completed so far (IPCC 2007, 2013; IMD 2010). During past 100 years, warming in India was more pronounced during winter season, and it was the minimum and not the

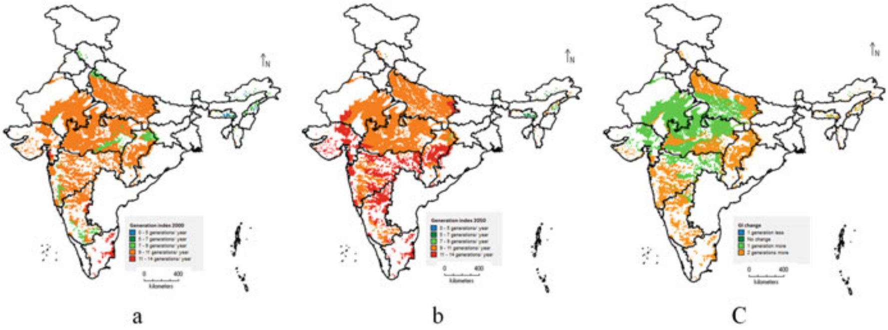

Fig. 15.2 Change in number of generations per year of *Spodoptera litura* in soybean growing areas of India based on generation index (GI). (**a**) Current climatic conditions, (**b**) future climatic conditions and (**c**) absolute change in GI. (For more details, please see Fand et al. 2015)

maximum temperature where significant increase was observed (IMD 2010). An average temperature increase of 1–5 °C is predicted for India by the end of 2100 (De and Mukhopadhyay 1999; Lal 2003; IPCC 2007, 2013; IMD 2010). This may affect the life cycles of insects which are undergoing a winter diapause as reported by Bale and Hayward (2010). At higher temperatures, the stored nutrients get depleted rapidly due to accelerated metabolic rates which further leads to the shortening of the duration of diapause (Hahn and Denlinger 2007). The temperature warming during winters may delay the onset of diapauses in insect species. On the other hand, if temperature gets warm during summer, it may lead to early termination of diapause in insects, which can then resume their active growth and development before their normal expected timings. Thus, climate warming would increase insect survival due to low winter mortality, increased population built-up and early crop colonizations that may lead to higher crop damage (Coulson et al. 2000; Harrington et al. 2001; Konestabo et al. 2007; Bale and Hayward 2010; Sharma et al. 2005, 2010).

15.2.4 Change in Manifestations of Host Resistance to Insects

Innate ability of crop plants to tolerate the damage due to insect pests without jeopardizing their yield potential is one of the key components of eco-friendly pest management (Painter 1968; Dhaliwal and Dilavari 1993). However, certain environmental factors like temperature, sunlight, soil moisture, air pollution, etc. significantly affect the degree of the host plant resistance. The abiotically stressful environment makes the crop plants more susceptible to damage by insect pests because of weakening of their own defensive system (White 1984). The occurrence of multiple stresses together influences plant physiological processes leading to decreased growth and also changes the allocation of resources and production of secondary metabolites in plants. The morphological and physio-biochemical changes that occur in plants under stress adversely affect in addition to growth and productivity, plants' defence response to insect herbivores feeding on them (White

1984). Plants which are under temperature and drought stress may become more susceptible to attack of insect herbivores due to decreased defensive compounds and widened nitrogen/carbon ratios in their leaves. Indeed, a variability that is seen in herbivore responses to host plant conditions may be species specific and, thus, preclude us from generalizing plant responses to different types of stresses and thus herbivore-plant interactions dependent thereupon. As the insect responses to stressed host plants are largely influenced by the magnitude of stress and feeding guilds exploited by insect herbivores, the future research programmes that focus on exact relationships between level of host plant stress and consequent insect performance are essential (White 1984). While planning for the experiments, we need to take into account the diversity of plant responses to various stresses to which they are exposed and apply different responses of insects with different feeding guilds to the stressed plants.

Breakdown of host plant resistance due to increased temperature and drought stresses has been widely reported (Rhoades 1985; Sharma et al. 2005; Volney and Fleming 2000; Logan et al. 2003). The increased temperature and water stresses have been predicted to intensify the yield losses in sorghum due to increased damage by midge fly *Stenodiplosis sorghicola* (Coq.) and spotted stem borer *Chilo partellus* Swinhoe (Sharma et al. 2005). Insect-resistant transgenic crop plants are the new hope for eco-friendly integrated pest management programmes. However, environmental factors like temperature, soil moisture and plant age influence to a greater extent the expression of insect toxins in transgenic plants (Dhaliwal and Dilavari 1993; Kranti et al. 2005). High temperature is reported affecting negatively the transgene expression in Bt cotton resulting in reduced production of Bt toxins resulting in increased susceptibility to bollworms, viz. *Heliothis virescens* (F.) (Kaiser 1996), *Helicoverpa armigera* (Hubner) and *Helicoverpa punctigera* (Wallen) (Hilder and Boulter 1999).

15.2.5 Shift in Manifestation of Resource Utilization

Insects are highly specific in utilizing plant resources and have adapted themselves to particular host niche exploitation as the host plant characteristics, which have been found to influence profoundly survival, reproduction and thus the population dynamics of herbivorous insects (Ohghushi 2012). The responses of various insects to use wide and heterogeneous plant resources are generally very specific. To illustrate, the insects adapted for exploiting plant foliage can rarely switch on to flowers and pods or fruits. Likewise, insects that are internal feeders like fruit borers, stem borers and gall makers are highly specialized to utilize these plant resources. These insects have synchronized their life cycles with that of the host plants on which they are feeding. Any small change or shift in synchrony of phenological events in insects and their hosts can affect profoundly the survivorship, abundance and population dynamics of insect pests. There exist vast majority of studies investigating the effects of phenological asynchrony on insect survival (Feeny 1976; Thompson and Price 1977; Auerbach and Simberloff 1989).

Fig. 15.3 *Spodoptera litura* larva feeding on pods of soybean (**a**) and damaged pods of soybean (**b**)

The climate change and associated weather extremes have been predicted to cause largely the asynchrony between phenologies of the insect pests and their host plants. Undoubtedly, this may influence the insect survival and abundance. However, chances are there that the insects may also switch on to utilize the available plant resources other than their routine feeding guilds. For example, in recent surveys conducted during kharif season of 2015 in soybean areas of Vidarbha region of Maharashtra state, the first author has found surprisingly the larvae of leaf-eating caterpillar *Spodoptera litura* damaging pods of soybean (Fig. 15.3). The pest so-called leaf-eating caterpillar usually feeds on leaves and causes extensive defoliation in many crops of economic importance like tobacco (*Nicotiana tabacum* L.), castor (*Ricinus communis* L.), cotton (*Gossypium* sp. L.), soybean (*Glycine max* L.), groundnut (*Arachis hypogea* L.), many vegetables and ornamentals (Moussa et al. 1960; Garad et al. 1984; EPPO 2013; CABI 2014). This pest is mainly defoliator and seldom reported to damage potato tubers and groundnut pods (CABI 2014). However, we could not get any published record documenting this pest damaging the pods or fruiting bodies of soybean. The reason for switching on to soybean pods by *S. litura* may be the possible life cycle asynchrony of pest insect and its host plant due to delayed monsoon and intermittent prolonged dry spells.

15.2.6 Increased Incidence of Insect-Vectored Plant Diseases

Sap-sucking insects like the aphids, whiteflies, jassids and thrips are supposed to be the major vectors for plant diseases, especially the viruses, accounting for transmission of about 90% plant virus diseases. The impact of climate change on geographic range distribution, survival and reproduction of insect vectors will ultimately determine the fate of viruses being transmitted (Petzoldt and Seaman 2010; Fand et al. 2012). Early season temperature increase leads to early colonization of aphids in potato, thereby increasing the risk of incidence of aphid transmitted virus diseases (Robert et al. 2000).

15.2.7 Asynchrony of Natural Biological Control

Biological control involving the use of natural enemies of insect pests such as predators, parasitoids and disease-causing entomopathogens has been important component of the integrated pest management programmes. However, being tiny and delicate, natural enemies of insect pests are more sensitive to climatic extremes like heat, cold, wind and rains. The increased drier conditions under future climate change may affect the performance of entomopathogenic fungi like *Beauveria bassiana*, *Metarhizium anisopliae* and *Lecanicillium lecanii*, which requires higher relative humidity for their better activity (Newton et al. 2011). Natural enemy and host insect populations may respond in different ways to changes in climate. Hosts may pass though vulnerable life stages more quickly at higher temperatures, reducing the window of opportunity for parasitism or predation which may give great set back to the survival and multiplication of dependent parasitoids and or predators, thus reducing the effectiveness of the natural biological control (Gutierrez et al. 2008; Petzoldt and Seaman 2010).

15.3 Key Challenges for Crop Growers

15.3.1 Emerging and Re-emerging Pest Problems

The spread of insect pests to new areas will pose a new challenge for the crop growers to deal with. More number of generations, increased population abundance and early crop colonizations due to shorter life cycles and early terminations of diapause under thermally stressed environments may result into increased frequency of insect outbreaks.

15.3.2 Reduced Effectiveness of Pest Management Strategies

Disruption of synchrony between insect pests and their natural enemies may upset the natural biological control of insect pests. The higher temperatures may lead to faster breakdown and dissipation of thermo-unstable chemical insecticides such as pyrethroids, organophosphates and the biopesticides rendering them less or no effective in controlling harmful pest insects. This will further lead to increased applications of insecticides and development of insect resistance.

15.3.3 Threat to Food Security for Mankind

The crop yield losses are expected to be intensified with aggravating pest problems under changing climate. Further, declining entomophilous pollination of field and horticultural crops under future climate warming is another yet important threat to sustaining the crop yields.

15.4 New Research Initiatives Required

15.4.1 Breeding Varieties that Are Resilient to the Climate Change

Development of new cultivars/varieties of crops that could sustain better under abiotically stressed environments and also resist to the attack of insect pests without jeopardizing their yield potentials is the need of hour.

15.4.2 Rescheduling of Crop Calendars

Shrinking of crop growing seasons and early crop colonizations by insect pests are likely to be more evident with the changing climatic conditions. Therefore the growers of the crops have to focus on the pest management strategies that suits better to the new situations.

15.4.3 Mapping of Pest Risks Using Geospatial Techniques

Geographic information system-based predictions and mapping of trends of potential changes in geographical distribution and delineation of agroecological hotspots and future areas of pest risk will serve as a guide to policy makers and pest management authorities in climate change adaptation planning.

15.4.4 Screening of Pesticides with Novel Mode of Actions

Exploring the chemical compounds having multiple roles such as pest control, plant growth promotion and tolerance to water and or temperature stress would be the novel approach for dealing the challenges of climate change and sustaining the crop productivity.

15.4.5 Understanding the Impacts of Climate-Related Extreme Events

Extreme events such as heat and cold waves have direct impacts on temperature values that affect insect development and their progenies. It is well known that temperatures below a certain value favour the development of males only, whereas temperatures surpassing a certain value may favour only females. Thus, changes in the incidence of extreme temperatures (high or low) through time could result in highly skewed population sex ratios. We therefore emphasize to carry out research activities to understand the effects of extreme temperature events in the overall population of insects.

15.5 Adaptation of Agriculture to Changing Pest Scenario Due to Climate

15.5.1 Stakeholder Sensitization

Organization of awareness campaigns, training and capacity building programmes, development of learning material and support guides for different risk scenarios of pest problems may be planned in order to sensitize the different stakeholders of agriculture such as farmers, extension workers, agriculture officers, etc. regarding the possible impacts of climate change on agriculture, its socio-economic consequences and adaption and mitigation strategies for the same.

15.5.2 Enhancing Adaptive Capacity of Stakeholders

The adaptive capacity of farmers could be enhanced by dissemination of knowledge and information regarding the current advances in the provision of weather and climate information and weather-based agro-advisory services for facilitating operational decisions at farm level.

15.5.3 Promotion of Resource Conservation Technologies

Conservation of natural resources can be promoted by giving incentives to the farmers those who are adopting environmental conserving pest controlling activities such as organic farming, biocontrol, integrated pest management, habitat conservation for important insect pollinators, etc.

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Food Chains and Webs: Interaction with Ecosystem

16

Gurminder Singh Chahil, Harsimran Kaur Gill, and Gaurav Goyal

Abstract

The interactions in an ecosystem depend on the characteristics of the interacting species. Species being the smallest unit of interest in an ecosystem, it is important to understand different types of species based on the role they play. The interactions between species can be beneficial or detrimental; positive, negative, or neutral; and horizontal or vertical. Overall community structure depends on the presence of one organism affecting the other. Several factors including taxonomy, morphology, physiology, environment, food, and interacting species shape the food chains and webs within an ecosystem. Most of the studies are done up to tritrophic levels, but the concept of food webs includes multitrophic interactions which are more complex to understand. The study of biotic and abiotic factors including light, moisture, temperature, resources, species, defense barriers, and environmental conditions gives more insight into the occurrence and alterations of the interactions in an ecosystem. Keeping these points in view, the present chapter has been prepared to give an understanding of species, food chains/webs, and ecosystem.

Keywords

Food chain · Food web · Ecosystem interaction · Multitrophic interaction

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16.1 Introduction

Plants are considered as the principal producers in any ecosystem, setting the stage for interactions in a community. For an ecologist, understanding the role of plants as food and habitat is important. The impact of plant characteristics is not only limited to herbivores, but toxins, attractants, and repellants may affect predators', parasites', and mutualists' activities too. These interactions are the building blocks of food chains in communities and ecosystems. A food chain, term coined and defined by Elton (1927), involves "chains of animals linked together by food, and all dependent in the long run upon plants." Food chains can be simple interactions of producer-herbivore-predator/parasite, but in real life, this interaction is more complex involving a number of food chains collectively called food webs in a community, which includes intermingling of interacting species at multiple trophic levels. Food webs are progression of communities into larger components of communities where sequences of feeding interactions or food (= energy) transfer takes place from primary producers to top carnivores at different trophic levels. A food web is an interwoven complex of a number of food chains. Food webs are constantly changing in space and time, have different frequencies and interaction intensities, and are ultimately simplified to only major interactions. The study of food webs generally involves the study of simple food webs which leads to oversimplification that may be misleading.

The concept of community can be defined as "an assemblage of populations that coexist in an area" (Root 2001). The concept of community may go beyond local habitat and extend to whole taxa of plants. The smallest unit of interest within a community is generally the species, and at times these are written under different names (foundation species, core species, dominant species, keystone species, structural species, ecosystem engineers), based on particular important role they play in an ecosystem (Ellison et al. 2005).

16.2 Interactions in a Food Web

It is critical to understand the interactions among organisms in a food web since the organisms can be negatively or positively affected by the presence of other organisms in the same environment. The effect on organisms due to the presence of other organisms affects the community structure. Few of such kind of interactions are discussed below:

16.2.1 Plants and Herbivores

Plants' and herbivores' interactions can be understood easily by knowing the concepts of taxonomic and ecological diversity of insect herbivores and their adaptable feeding behaviors and plant's nutritional, structural, and chemical barriers (allelochemicals) to herbivore attack. Such information can be exploited for better

Table 16.1 Classification of terrestrial insect orders based on the feeding strategy and parts of plants eaten in exposed or concealed locations

Feeding type	Feeding strategy	Parts of plant	Major insect orders
Chewing	Exophage	Exposed locations: leaves, flowers, pollen, seed heads, and fallen seeds	Lepidoptera (moths and butterflies), Coleoptera (beetles), Orthoptera (grasshoppers), Hymenoptera (sawflies and ants), and Phasmatodea (stick insects)
Chewing	Endophage	Concealed locations: within living, dying, or dead plant tissues	Lepidoptera (leaf tiers, leaf rollers, leaf miners); leaf miners (Coleoptera, Diptera, Hymenoptera, Lepidoptera); Lepidoptera, Coleoptera, and Hymenoptera (stem borers); Coleoptera, Lepidoptera, and Hymenoptera (wood borers); Diptera and Lepidoptera (fruit borers), and Coleoptera, Lepidoptera, and Hymenoptera (seed/pod borers)
Sap feeders	Exophage	Various plant tissues	Hemiptera, Thysanoptera (phloem feeders (phloem feeders, e.g., aphids, planthoppers, treehoppers, leafhoppers, scale insects, and xylem feeders (cicadas, spittlebugs) and epidermis/mesophyll/parenchyma feeders)

Adapted from Gullen and Cranston (2005)

management of insect pests of agricultural and forest ecosystems which will help in saving crops from herbivore damages worth billions of dollars every year. Herbivores can be categorized on the basis of their host range and number of species attacking same resource (feeding guild) and can be monophagous (specialists; feed on a single plant species or on the same genus), oligophagous (feed on several plants genera, within the same family of plants), or polyphagous (generalists; exploit plants in many families). Different factors such as mouthpart (chewing and piercing-sucking), microhabitat (stems, leaves, fruits, seeds bark, dead wood, roots, detritus, and fungi), and manipulations of attacked plant materials (leaf tiers, rolling, galls, shredding, and scraping) ultimately affect feeding guilds (Tables 16.1 and 16.2).

16.2.2 Horizontal Interactions: Competition, Facilitation, and Mutualism

Interactions that occur among individuals feeding at the same trophic level are called horizontal or lateral interactions which in the case of insect herbivores can be negative (competition or amensalism), neutral, or positive (facilitation and mutualism) (Kaplan and Denno 2007). Negative interactions occur when either both species are negatively affected (−, −) as in competition or when one of the interacting

Table 16.2 Classification of aquatic insect orders based on the feeding strategy and habitat

Aquatic insect categories	Function	Insect orders
Shredders	Feed on living or decomposing plant tissues; break up detritus into smaller fragments, making it available for collectors	Plecoptera, Trichoptera, Coleoptera, Diptera
Collectors	Feed on plant fragments and decomposing bits of organic matter smaller than those usually consumed by shredders	
	Filter feeders: strain minute particles from the water column	Diptera (blackfly larvae), net-building Trichoptera
	Gatherers: feed on organic matter on the streambed	Ephemeroptera, Coleoptera, Trichoptera, Diptera
Scrapersi	Graze on surface vegetation or on algae that is attached to submerged substrates	Ephemeroptera, Coleoptera, Trichoptera, Lepidoptera, Diptera

Adapted from Gullen and Cranston (2005), and Merritt and Cummins (1996)

species suffers but the other remains unaffected (−, 0) as in amensalism. Facilitation in which at least one species benefits from the interaction (+, 0) and mutualism in which both participants benefit (+, +) are types of positive interactions (Bruno et al. 2003). Begon et al. (2006) defined competition as “an interaction among individuals, generated by a shared requirement for a limited resource that leads to reduction in the growth, reproduction or survival of the individuals involved.” Competition for inadequate resources such as food, shelter, and oviposition sites ultimately prevents population growth via adverse density-dependent impacts on fecundity and survival, unless limited by other climatic and biotic factors. Intraspecific competition involves interactions over a shared resource within individuals of the same species, while interspecific competition interactions occur among individuals of different species. Nicholson (1954) divided competition into exploitative (scramble) and interference (contest) competition. Exploitative competition can lead to resource depletion and occurs when different individuals have access to a limited resource. Interference competition occurs when some individuals try to access more than their share of resources and in so doing take away access of other individuals by direct killing, production of chemicals, and aggressive displacement. For example, smaller females are deprived off of oviposition sites by the larger females of the gall aphid (*Pemphigus betae*) on leaves of narrow leaf cottonwood (*Populus angustifolia*) (Whitham 1979). Quiring and McNeil (1984) also reported density-dependent interference competition in larvae of the alfalfa blotch leaf miner (*Agromyza frontella* (Rondani)).

Facilitation involves the significant diversity of effects in which one species may improve conditions for the member of same or different species feeding on the same food (Denno and Kaplan 2007). The combined predation rate of ground beetle (*Harpalus pennsylvanicus*) and lady beetle (*Coccinella septempunctata*) was nearly double the sum of their individual predation rates on pea aphid (*Acyrthosiphon pisum*) in a laboratory mesocosm (Losey and Denno 1998). Similarly, increased group resistance and survivorship was reported in eusocial insects like damp wood termites (*Zootermopsis angusticollis*), when exposed to entomopathogenic fungus (*Metarhizium anisopliae*) (Traniello et al. 2002). This facilitation was attributed to the increased grooming, removal of diseased individuals from colony, and the innate and adaptive immune responses of the members of termite colony.

Mutualism involves association of two species in which both interacting species are benefitted. Such species may live in symbiotic mutualism where close association lasts through much of their lives. Most classical examples include microbial symbionts of insects such as termites and their gut microfauna (protozoan and bacteria). Mutualism is obligate when a compulsory association is required for the survival and reproduction of a species (termites and microbes). Two bacterial symbionts, a *Wolbachia* strain and an unnamed γ-proteobacterium, associated with different strains of the bedbug (*Cimex lectularius*) show obligate nutritional mutualism (Hoshokawa et al. 2010). The bedbugs were reported to have retarded growth and sterility when the symbionts were eliminated from their body. The mutualism is facultative when association is not essential for survival and reproduction. Stick insects (phasmids) and ants in Australia show facultative mutualism in which eggs of stick insect are dropped from the tree canopy to the ground. The ants are attracted to capitula on the eggs, and they carry eggs into their nests to protect them against natural enemies (Hughes and Westoby 1992).

16.2.3 Interactions Among Prey, Predator, and Parasitoid

Consumption of one living organism (the prey) by another organism (the predator) is called predation, and in this process the whole prey is killed and eaten. Usually invertebrate preys are considered as preys, but this term can also extend to plants when they are in seed or seedling stage which can be consumed as a whole. This definition distinguishes predators (e.g., beetles) from parasitoids (small wasps and flies); predators require and eat only one prey item during their life span. However on the other hand, an adult female parasitoid oviposits and is ultimately responsible for mortality of many hosts (more than one unlike predators). Parasitoids lay eggs in or on a host and are free-living as adults. After hatching in the host, larvae live parasitically in or on the host, eventually killing it. Predators are generally kept at functionally distinct levels above the prey (herbivore) but may consume not only the prey but also other predators and/or plant resources. Therefore, generalist predators are also called omnivores or the consumers that feed on multiple trophic levels. For example, generalist predator strawberry seed beetle (*Harpalus rufipes*) is omnivorous and feeds on prey including aphid, lepidopteran eggs and larvae, seeds, pods, and leaves of many plant species. Similarly, fire ants prey upon big eyed bugs (*Geocoris* spp.) in addition to herbivorous preys. This kind of omnivory where one predator preys upon other predators is known as intraguild predation. Another kind of predation where predators consume members of their own species is called cannibalism. Flour beetles (*Tribolium* spp.) and cricket (*Anabrus simplex*) and many other insects are known for cannibalism (Simpson et al. 2006). These kinds of interactions increase the food webs complexity and complicate the role of predators in community dynamics.

Mostly predators are generalists, but they can also be specialists like larvae of hoverfly (*Parasyrphus nigritarsis*) which get attracted to the noxious volatile larval secretions of two prey species Brassy willow beetle (*Phratora vitellinae*) and Alder leaf beetle (*Linaeidea aenea*) (Kopf et al. 1997). Whether predators are generalists or specialists, they do affect prey populations which can be significant in some cases. Predaceous ladybird beetles (*Rodolia cardinalis*) used for biological control of cottony cushion scale (*Icerya purchasi*), an introduced pest of citrus from Australia which severely threatened the California citrus (*Citrus* spp.) industry in the late 1800s, is a classic example of pest population suppression (Caltagirone and Doutt 1989). Interactions between the predator and prey determine long-term population dynamics of each species. In this example 100 years of the study revealed that specialist predator the clerid beetle (*Thanasimus dubius*) is responsible for decreasing pine beetle (*Dendroctonus frontalis*) population, and ultimately the predator beetle also decreases in a cycle of 10 years. After some time pine beetle population recovers and so the clerid beetle population and cycle go on (Turchin et al. 1999).

16.2.4 Additive, Antagonistic, and Synergistic Interactions

In nature, prey and predators do not interact with each other individually but are nested within complex food webs of interacting species. Different predator species occurring simultaneously, within a community, can affect other interactions in a food web. The effects are additive when there is no impact and prey consumption in this case can be determined by simply adding the number of prey consumed by each predator species when present alone. For example, in alfalfa (*Medicago sativa*) crop in the USA, pea aphids (*Acyrthosiphon pisum*) are attacked by generalist predators like carabid beetles, bugs (*Nabis* spp. and *Orius* spp.), coccinellid beetles, web-building spiders, and specialist parasitoid wasp (*Aphidius ervi*) (Snyder and Ives 2003). Predation has been reported to have additive effects on reducing population of the aphids.

In a manipulative field experiment in artificial ponds (in the USA) antagonistic impact of larvae of a migratory dragonfly (*Tramea lacerata*) on a native dragonfly species (*Erythemis simplicicollis*), feeding on damselflies was recorded (Wissinger and McGrady 1993). The damselfly consumption by *E. simplicicollis* reduced to half in the presence of *T. lacerate*. Similarly, in a study to infest creeping thistle weed (*Cirsium arvense*), with the rust fungus (*Puccinia punctiformis*), three herbivorous insects, the aphids *Aphis fabae* and *Uroleucon cirsii* and the beetle *Cassida rubiginosa*, were released. The fungus *P. punctiformis* spore material was mechanically transported by all the three insects and also significantly increased rates of infection in healthy thistles. But the interaction between *C. rubiginosa* and the fungus was antagonistic where biomass of adults was significantly reduced and mortality increased when feeding on plants infected with *P. punctiformis* (Kluth et al. 2002).

16.2.5 Host-Parasite Interactions

A parasite can be defined as an organism living in or on another living organism, obtaining its nutrition from that host organism and causing some degree of measurable damage to the host. Parasitoids are organisms that have free-living adults that find insect hosts, on or in which they deposit eggs or living larvae. The larvae develop in a parasitic manner in the living host, whether the host continues to feed or lie in a moribund state, paralyzed by the adult parasitoid. In either case, the host is killed eventually by the parasitic stage. Therefore, the adult parasitoid results in the death of many host insects, and its actions are equivalent to those of a predator. Some of the common definitions of host-parasite/parasitoid interactions defined by Price et al. (2011) are given below:

1. *Autoparasite/Adelphoparasite*: Some parasites parasitize other members of the same species, as seen in the hymenopteran (*Coccophagus scutellaris*). The male is an obligate autoparasite of the female (van den Bosch et al. 1982).
2. *Kleptoparasite*: A species that takes away food from other species (social parasitism in insects such as in cuckoo bees). True kleptoparasitism is common in parasitoids, e.g., wasp (*Argochrysis armilla*) (Rosenheim 1987).
3. *Hyperparasitoid*: A parasitoid that attacks a host already parasitized by a primary parasitoid and can also parasitize the primary parasitoid, e.g., wasp (*Lysibia nana*) (Harvey et al. 2007).
4. *Idiobiont*: A parasitoid in which the host is permanently paralyzed by the adult parasitoid. The eggs hatch, and the parasitoid feeds on the moribund host, e.g., *Dendrocerus carpenter* (Hymenoptera: Ceraphronidae) (Otto and Mackauer 1998).
5. *Koinobiont*: A parasitoid that lives with the living host, when the host continues to feed and to defend itself, e.g., parasitic wasp (*Aphidius colemani*) (Lykouressis et al. 2009).
6. *Multiparasitism*: When host is attacked by more than one species of parasitoid.
7. *Parasite*: Insects that live on, or in, and feed on a single living plant or animal for long periods of time, or for most of their lives, sapping energy from the host and causing damage.
8. *Parasitoid*: Parasite insects feeding on a single host until maturity and kill the host eventually. Adults are free-living, finding living hosts and laying eggs in, on, or near them.
9. *Pathogen*: A species that causes disease in other species, usually applied to viruses, bacteria, protozoa, or fungi, whether they parasitize plants or animals.
10. *Superparasitism*: When more eggs are laid on or in a host than can be supported by the resources of that host. Eggs may be from the same or different species.

16.2.6 Multitrophic Interactions

Multitrophic interactions link more than two trophic (T) levels, including plants (T1), herbivores (T2), and predators, parasitoids, or pathogens (T3 and beyond). Most commonly studied interaction levels are tritrophic interactions, when three trophic levels are involved. Food webs typically go beyond three trophic levels, with higher-order predators preying on intermediate predators and hyperparasitoids attacking primary parasitoids, so the term "multitrophic interaction" is used for more complex food web dynamics. Trophic levels represent the hierarchical positioning of organisms in a food chain. Lindeman (1942) originally devised this hierarchical system to group organisms with similar functional roles in a food web, an approach that is commonly employed in ecology. Producers (plants) as base resource represent trophic level one (T1), while primary consumers (herbivores) feeding on producers are second trophic level (T2), secondary consumers (carnivores) eat primary consumers (T3), and this goes on to higher trophic levels. In theory, this linear chain describing who eats whom can extend indefinitely to the tertiary consumers, the fourth trophic level (T4), and beyond, depending on how many consumers exist in a given community. Such concepts of simple linear food chains however suppress the inherent complexity of real communities, the complexity that is largely driven by the presence of omnivores that feed from multiple trophic levels.

16.3 Factors Affecting Interactions in Food Web

A number of factors can affect the interactions in a food web or in an ecosystem. These factors also depend on the sexes, feeding habits, habitats, and life history of an organism. For example, caterpillars are herbivores, but adult butterflies are mostly pollinators; immature mosquitoes are aquatic, while adults are terrestrial, and even male and female mosquitoes have different feeding preferences. In different ecosystems, changes in abiotic and biotic parameters of prey-predator relationships can alter the outcomes of species interactions (Holland et al. 2009). The strength of interaction depends on the proximity, relative densities, motivation, and ability of interacting species to perceive each other. These factors in turn are affected by abiotic conditions such as resource availability and indirect effects of other species.

16.3.1 Abiotic Conditions

Many studies have addressed the effects of abiotic conditions, like temperature, light, and moisture, on species interactions. Changes in temperature may affect interactions at various trophic levels. Increased activity of grasshoppers in hot and sunny places as compared to cold and shade was recorded as compared to its predatory spider which was unaffected by the temperature and sunlight (Logan et al. 2006). Preisser and Strong (2004) reported that variation in soil moisture directly affected populations of root-feeding ghost moth (*Hepialus californicus*) and its host, yellow bush lupine (*Lupinus arboreus*), and outbreaks were more severe in drought conditions. Plants may benefit from increased exposure to sunlight which can induce production of defensive compounds and ultimately reduce herbivory (Niesenbaum 1992). Abiotic factors may also adversely affect plant defense systems. For example, susceptibility of St. John's wort (*Hypericum perforatum*) to herbivores was reported to increase with drought (Fox et al. 1999). Similarly, other abiotic factors like CO_2, O_3, NO_2, or SO_2 may affect interactions in a food web.

16.3.2 Availability and Distribution of Resource

Resource availability and distribution regulate populations, competition, and predation, within and between different trophic levels. Resource abundance leads to increased consumer population and increase in interspecific competition at intermediate levels of resource availability. Populations increase to a certain level (population outbreak) at which point consumption of available resource is maximum. At this point the resource availability starts decreasing and also reduces populations of competing species. Scarcity in resources supports low population density of related species which leads to search for more suitable resources which in turn limits growth, survival, and reproduction of the related species. Under these conditions, potentially interacting species are parted in time and space which may lead to migration. This minimizes competition and maximizes predator-free space. In contrast, more homogeneous environments facilitate population spread of associated species and maximize the probability of co-occurrence. In East Africa, four termite (order: Isoptera) species that reside on acacia (*Acacia drepanolobium*) are reported to reside on individual tree with violent interspecific competition for host trees by adjacent colonies (Palmer 2003). The competition was variable relative to distance of termite mounds from the resource (acacia trees). The competitively dominant ant (*Crematogaster sjostedti*) displaced other acacia ants (*Crematogaster mimosae*, *Crematogaster nigriceps*, and *Tetraponera penzigi*) near termite mounds, whereas the probability of subordinate species displacing *C. sjostedti* increased with distance from termite mounds. This variation in the outcome of competition for acacia hosts appeared to result from differential responses among the ant species to resource heterogeneity on the landscape.

16.3.3 Indirect Effects of Other Species

Indirect interactions have received less attention but may be as important as direct interactions. For example, pollinators can augment plant reproduction sufficiently to compensate for herbivory. Bezemer et al. (2005) reported that manipulation of soil nematodes and microorganisms significantly altered the amino acid and phenolic content of plants, thereby altering aphid and parasitoid performance. Because multispecies interactions control rates of energy and nutrient fluxes through ecosystems, resolution of the extent to which indirect interactions reduce variation in community structure will contribute significantly to our understanding of ecosystem stability. Herbivore-induced defenses can affect interactions with other members of the community, as well. Callaway et al. (1999) reported that the tortricid moth (*Agapeta zoegana*) introduced to the Western USA for biological control of spotted knapweed (*Centaurea maculosa*) increased the negative effect of its host on native grass (*Festuca idahoensis*).

16.3.4 Defense Barriers at Different Trophic Levels

Herbivores constitute more than half of insect fauna of the world, but these are restricted to only 9 (~30%) out of 29 insect orders (Gullen and Cranston 2005). This advocates that plants have evolved defense barriers to insect attack which include nutritional, mechanical, and allelochemical defenses, plant phenology, and spatial distribution that render plants inherently difficult to exploit. Plants possess a variety of ecologically important traits that may affect interactions in a food web. These plant traits are supposed due to the presence of secondary plant metabolites (allelochemicals) that play no role in plant growth, development, and reproduction but affect plant interactions with herbivores and higher trophic levels. Secondary metabolites attract, repel, poison, or harm insects and can be classified into toxins, digestibility reducers, and volatiles. These are useful in their induced state as they help attract natural enemies to the specific location of their prey. Toxins (alkaloids, glucosinolates, cardenolides, and furanocoumarins) when ingested at sufficiently high doses may poison and even kill the consumers. In a classical example, monarch caterpillars (*Danaus plexippus*) sequester cardiac glycosides from their milkweed host plants, which help protect the adults from bird predation (Brower et al. 1967). Contrary to providing protection, toxins sometimes show negative response for protection from enemies. For example, the leaf beetle (*Chrysomela lapponica*) feeding on salicyl glucoside (SG) content from willow (*Salix* spp.) trees is more prone to attack of phorid and tachinid flies (Zvereva and Rank 2003).

Volatiles are among other important plant traits to be integrated with digestibility-reducing chemicals (otherwise known as volatile organic compounds or VOCs) for plant defense. These are species specific and can be detected several meters or more from their source plant and provide reliable cues for insects to exploit in search of food. Predators and parasitoids are both known to use plant volatiles in their foraging decisions and also use array of cues while searching for prey, including those derived from the herbivores (such as frass). Volatiles are ubiquitous, multifunctional in nature, i.e., repel herbivores, attract pollinators, and act as within-plant signaling compounds. Baldwin (1998) found that survival of tobacco hornworm (*Manduca sexta*) eggs declined from 83% on control plants to 4% on plants with induced volatiles which was directly attributed to attraction and increased predation by the hemipteran predator (*Geocoris pallens*). The corn plants release a compound (E)-b-caryophyllene due to mechanical injury or the feeding from larvae of the western corn rootworm (*Diabrotica virgifera*), important pest of corn, that attracts their nematode parasites (Rasmann et al. 2005).

16.3.4.1 Nutritional Barriers

In all living organisms, carbon (C), nitrogen (N), and phosphorus (P) are the major elements, but the relative balance of these elements in food differs at different trophic levels. Importantly, nutritional imbalances created by organisms feeding at lower trophic levels on nutrient-deficient (N and P) food can severely hamper their ability to meet nutrient demands, growth, and reproduction. For example, herbivores and detritivores have five to ten times higher nitrogen (N) and phosphorus (P) contents than their host (Denno and Fagan 2003). Nitrogen content (%) and C:N (carbon/nitrogen) ratio between plants and insect herbivores have been recognized as imposing fundamental limitations on nitrogen acquisition (Awmack and Leather 2002). The planthopper (*Prokelisia dolus*) has been reported for severe constraints on growth due to limitations of N and P content of host plants (Huberty and Denno 2006). Plant nutritional resources can be classified into (a) traits that are adaptations for growth and reproduction (e.g., leaves, flowers, and fruits) and (b) structures that are thought to have evolved for the sole purpose of maintaining large enemy populations as bodyguards (e.g., extrafloral nectaries, food bodies). Plant traits that may have coevolved (extrafloral nectaries and food bodies) with natural enemies serve the purpose of attracting predators and parasitoids and thus providing protection to plants against herbivores. They serve no role in primary metabolic processes of plants for growth and development. Extrafloral nectaries are small openings purposefully positioned on petiole or midribs of leaves, stems, bracts, and fruits of angiosperms and are known for exuding nectar consisting of sugars like glucose, fructose, and sucrose. These are visited by ants, lacewing larvae, non-web-building spiders, and many other nectar-loving natural enemies. Food bodies are small epidermal structures rich in proteins and lipids that are harvested by foraging ants and some non-ant species (Fiala and Maschwitz 2008). They also suggested that ant-plant interactions are enhanced by food bodies. Where nectaries are visited by a diverse assemblage of consumers (facultative mutualism) on myrmecophilic plants (plants which lives in a mutualistic association with ants), the food bodies are harvested by ants (obligate mutualism) on myrmecophytic plants. The obligate mutualism involving food bodies is more of a symbiotic interaction, where the ants and plants in many cases cannot survive in the absence of the other. It differs from facultative mutualisms in which both partners may benefit from the association, but are not dependent on one another for survival.

16.3.4.2 Mechanical Barriers

Plants possess a variety of mechanical features and structures (general tissue toughness and hardness, trichomes, and surface waxes) that pose physical-chemical barriers to herbivore attack (Keeping and Kvedaras 2008; Lucas et al. 2000). In general, young leaves are less tough than mature leaves, due to number of factors associated with it such as leaf thickness, the amount of cellulose and lignin, and the structural components of plants (Peeters 2002). Diversity in density, shape, size, and forms of trichomes protects plants from herbivore attack, although their effectiveness may vary with circumstances (Handley et al. 2005; Pott et al. 2012; Valverde et al. 2001). Overall, trichomes affect insect herbivores by influencing oviposition, movement, growth and fecundity, and their interactions with higher trophic levels (Andres and Connor 2003).

Trichomes are small, epidermal hairs on leaves, stems, and other plant parts that serve as physical barriers hindering insect movement or may be associated with glands that express secondary compounds in viscous secretions exuding from the trichome tips to trap small insects. Plant species and genotypes differ in trichome length, density, and ratio of glandular to non-glandular hairs. For example, glandular trichomes of sacred datura (*Datura wrightii*) repel several whitefly species, while phylogenetically related bug mirid (*Tupiocoris notatus*) performs better on and prefers glandular trichome-bearing plants (van Dam and Hare 1998). Sometimes plants selectively encourage survival of natural enemies in special morphological structures called domatia, which insects use as refuge or housing for a mutualistic association. Mutualisms of ants and mites with domatia-bearing plants are good examples. Cavities, cracks, and crevices that are naturally formed in stems, branches, roots, galls, leaves, and bark are examples of such structures where opportunistic species establish their nests (Holldobler and Wilson 1990).

16.3.4.3 Defense Through Evolution

A wide range of defense mechanisms are present in prey species which can be categorized as primary, secondary, or tertiary depending on how they handle detection, capture, or handling by predators. With effective defenses, the prey evades detection from predators by a wide variety of morphological and behavioral mechanisms like concealing to match the environment, hiding their feeding damage (e.g., eating an entire leaf), or removing frass that accumulates at their feeding sites. For example, the green coloration of grasshoppers (family: Orthoptera) matches with the background vegetation (eucrypsis); the prey resemblance to an inedible food source of the predators, as in case of early instars of caterpillars of *Papilio* spp. mimicking bird droppings (mimesis), helps in primary protection. Sometimes unpalatable prey species may utilize the opposite strategy by advertising their unacceptability to predators using conspicuous smells, sounds, or coloration (aposematism). The evolutionary convergence in appearance, sound, or smell of unpalatable species is referred to as Mullerian mimicry. In this case, unrelated noxious species that are also prey to a common predator are avoided by the predator. When a palatable prey species is benefitted due to its appearance to an unpalatable prey species, this type of deceit is referred to as Batesian mimicry and is defined as the evolutionary advergence in appearance, sound, or smell. African swallowtail butterfly (*Papilio dardanus*) is a palatable species and subject to heavy predation by birds, but the occurrence of different species of distasteful mimetic morphs of *P. dardanus* females over different geographical range benefits the palatable one (Price et al. 2011).

16.4 Trophic Cascades

Strong (1992) defined "Trophic cascades mean runaway consumption, downward dominance through the food chain." Generally, trophic cascades are the indirect positive impacts of natural enemies on lower trophic levels, via suppression of herbivores. For this definition to be true, two fundamental conditions must hold true. Firstly, herbivores must suppress producer (plant) growth in the absence of natural enemies. Secondly, enemies must function collectively as a cohesive third trophic level, reducing the abundance of their herbivorous prey and releasing plants from the potentially devastating effects of herbivory. But in real world, plants may contain toxic chemicals and other factors like structural carbon which render them relatively inedible to herbivores. Similarly in real food webs in nature due to intraguild predation, omnivory and other complexities can affect the performance of natural enemies. Thus, strong cascading effects are expected when plants are relatively palatable and enemies attack herbivores instead of one another. Cascades weakly exist, and assumptions are violated in cases of strong plant defense mechanisms and heavy intraguild predation.

A number of biotic and abiotic factors influence each trophic level in a community which affects the outcome of different interactions. The strength of cascades either up or down the food web depends on the heterogeneity in extrinsic and intrinsic variables at any given trophic level. Three general circumstances are hypothesized to promote top-down cascades on plants. These include:

16.4.1 Suitable Environmental Conditions

Environment comprises of a wide range of variables which can act directly or indirectly on multiple trophic levels. These factors include relative humidity, temperature, light, nutrients, water, carbon dioxide, soil properties, and other disturbances. At moderate and low soil fertility, herbivores were reported to change the ranking of plant species by suppressing the palatable grasses (*Lolium perenne*, *Poa annua*, and *P. trivialis*) and promoting plant species with slower growth rate (*Festuca rubra*, *F. ovina*, and *Anthoxanthum odoratum*) (Buckland and Grime 2003) They also reported that carnivory of ladybird beetles and their larvae persisted in relation to ground beetle (*Pterostichus melanarius*) activity. Natural enemies are considered relatively more vulnerable to environmental stresses compared with herbivores. So we can predict strong top-down effects in low stress habitats, while moderate to high stresses will result in weak cascades thoroughly. Understanding of the basic biology is sometimes very important to study impact of environmental stresses on different trophic interactions.

16.4.2 Inherent Characteristics of Consumers and Resources

Producers, herbivores, and natural enemies each possess a suite of diverse inherent attributes that may promote trophic cascades. Foraging behavior is one such feature of predators and parasitoids based on which insects can be categorized into actively foraging (e.g., coccinellid beetles, lacewings, etc.) and sit and wait (e.g., most spider species) predators. Where the sedentary herbivore populations may be effectively regulated by actively foraging predators, the sit and wait predators are unlikely to suppress such populations. The sit and wait category includes omnivorous top predators, which generally suppress populations of widely foraging intermediate predators and thereby increasing herbivore densities. The tendency to protect host range is another characteristic in foragers where specialist parasitoids tend to protect plants more effectively than generalist or polyphagous species.

16.4.3 Multichannel Omnivory

Polis (1999) suggested that multichannel subsidies (input resources like insect prey, leaf litter) produce more consumers than can be supported by the resources and these consumers then depress their resources. Subsidies originate outside the delineated food web and can be classified into three general categories: spatial, temporal, and detrital. Spatial subsidies involve the movement of resources produced in one habitat to the adjacent habitat, where they promote consumer abundance and thereby strengthen trophic cascades in the recipient habitat (Leroux and Loreau 2008). Cicadas emerge from the soil every 13 or 17 years, and their carcasses are deposited into watercourses subsidizing aquatic ecosystems (Menninger et al. 2008). Temporal subsidies elevate consumer populations temporarily through resource pulses. Mature oak (*Quercus* spp.) trees, a preferred food of white-footed mice (*Peromyscus leucopus*), produce large acorn (*Quercus* spp.) crops, referred to as masting, every 2–5 years in the USA. Masting in the autumn increases survival and breeding of mice in the succeeding winter and spring. As mice are predators of gypsy moth (*Lymantria dispar*) pupae, the masting helps reduce moth pupae in the subsequent year. These periodic pulses of oak acorn also help reducing Lyme disease transmitted by ticks (Ostfeld et al. 2006). Detrital subsidies may allow higher population densities of generalist predators that will contribute to stronger cascades in grazing food webs (Miyashita et al. 2003). Examples of detrital subsidies include natural spider control of planthoppers in tropical rice agroecosystems, and local subsidies similar to detritus include honeydew exudes of hemipterans which subsidize omnivorous hymenoptera.

16.5 Food Web Understanding in Agriculture, Conservation Ecology, and IPM

Understanding of food webs is important for maintaining balance in ecosystem. Though these are highly complex systems, basic knowledge of cropping patterns and consumers present at higher trophic levels can help in devising strategies for pest management. Understanding basic biology and ecology of producers and consumers can help predict probable problems that may arise in an agricultural system. Pesticides and other agricultural inputs sometimes have detrimental effects on different organisms interacting in the environment. This also affects natural enemies of insect pests and weed. Weed seed predators like *H. rufipes* were reported susceptible to field rates of some commonly used pesticides of older chemistry as compared to newer chemicals used in lowbush blueberry (Cutler et al. 2016). Conservation ecology helps study such effects and find alternatives for sustainable agriculture. Some of the important points involving the understanding of food webs are listed below which can help in improved agricultural management with the basic understanding of simple food chains and food webs.

16.5.1 Insects in Environmental Monitoring and Assessment

Insects are virtually present in all environments of interest, the above and below ground surface, aquatic habitats, wild and urban environments. Environmental assessment and environmental impact rely on sound-monitoring techniques. Long-term studies of species and communities are particularly valuable for detecting trends in populations and biodiversity correlated with abiotic and biotic variables such as land use, habitat destruction, and climate change. The climate change, conservation, biodiversity, and sustainable environments are studied to estimate health of communities and their long-term maintenance. Various insect species can be employed as indicators for the assessment of environment, degradation, or recovery. The conservation of ecology or maintaining biodiversity is the central theme during any environmental modifications.

16.5.2 Indicator Groups and Species

Focus on a particular insect taxon (indicator groups and indicator species) like butterflies, dragonflies, ants, or aquatic groups can be useful in observing any change in the ecology of the area under observation. Here the concepts of the ecological niche (defined as behavior of species living under specific environmental conditions) and guild (any species group that exploit the same resources often in related ways) become useful. Guilds of species may be employed as indicator groups, and several guilds could be used to monitor environmental conditions such as checkerspot butterflies (McLaughlin et al. 2002) or/and ants (Forys and Allen 2005).

16.5.3 Agricultural Practice

Human activities have changed community ecology. Though agricultural practices have simplified habitats, they had reduced nesting sites and food supplies for some kinds of insects. For example, nesting sites for twig-dwelling ants (family: Formicidae) were destroyed when dense-shady canopy of native trees was removed in coffee (*Coffea* spp.) plantations. The example of biological control of cottony cushion scale (*Icerya purchasi*), with *R. cardinalis*, is a classic example of biological control. However, introduction of insect growth regulators (IGRs) in the late 1990s caused high mortality of *R. cardinalis*, and cottony cushion scale reemerged in high numbers. So, integrated pest management (IPM) should include the use of reduced risk pesticides on crops (Gill and Garg 2014; Cutler et al. 2016). These pesticides are safe to the natural enemies and can play an important role in conservation ecology.

16.5.4 Restoration Ecology

Ecological restoration of an ecosystem is the approximate return to its structural and functional condition before damage occurred, and it depends on concepts of community ecology particularly approaches and concepts related to ecological succession and ecological assembly (Young et al. 2005). This required extensive knowledge of food webs and community ecology such as how the community develops and mechanisms driving activities of members. The restoration plan or better prospective restoration should incorporate a project ensuring a sustainable ecosystem well into the future. For integrated pest management, for example, in the biological control of insects, and weeds, attempts should be made to establish communities of natural enemies on these pest species. Promoting natural populations of granivorous insects in some cropping systems can be of valuable ecological service in managing weeds (Cutler et al. 2016).

16.5.5 Selection of Cropping Patterns

Producer (mostly plants) characteristics at the first trophic level impact survival in succeeding trophic levels as well as consumers' capacity to locate, capture, and consume hosts. One of the important principles of integrated pest management is that different strategies should not counteract with one another and try to synergize effects of other tactics. Subsidizing enemy diets with nutritional rewards by enhancing vegetation diversity, such as border or companion crops, cover crops, and intercropping, is the other main driver in the application of multitrophic interactions for pest management. Habitat management might support the abiotic environment for natural enemies.

16.6 Conclusion

In present times when the world is struggling to feed the ever-increasing global population, knowledge of species interactions in an ecosystem can be exploited for better management of crops. Crops worth billions of dollars can be saved from the damage done by insect pests of agricultural and forest ecosystems every year. For this purpose, a good understanding of the role played by different species at each trophic level needs to be understood. As discussed in the chapter, even a single organism plays different roles in a food web. Understanding of the key components of the ecosystem can help us devise ways to maintain ecological balance. For agriculture sustainability, emphasis should be on conservation studies to maintain ecological balance. In this regard, different cropping systems, cropping patterns, indicator groups, disturbances, and species at each trophic level, which can provide valuable conservation and ecological service, should be studied.

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Future of Rice Crop Under Enriched CO_2 Environment

17

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Abstract

Rice (*Oryza sativa* L.) is the second largest cereal crop produced globally, with a worldwide production of about 720 million metric tons in recent years and contributing toward for 20% of the global calorie intake. The growing condition of rice is extreme such as high vs. low temperature and high vs. low level of CO_2 concentration [CO_2]. Given CO_2 is a key substrate for photosynthesis, the atmospheric concentration of CO_2 dominantly influences the growth and yield of rice crop. The main component of rice is the kernel (~90%) which is starch, and the composition and behavior of starch are greatly impacted by environmental drivers including temperature, CO_2, and water. Therefore, it is important to understand the variation in production and yield of rice under the elevated [CO_2]. Here, we discussed the impacts of elevated [CO_2] on the quality and quantity of rice production under current and future climatic conditions. We have discussed the response of rice crops under elevated [CO_2] and its interaction with several other biophysical drivers including air temperature, ozone concentration, soil water content, and genotype in various experimental approaches, viz., free-air CO_2 enrichment (FACE), open top chambers (OTC), growth chambers, and temperature gradient tunnels. Overall, elevated [CO_2] stimulated photosynthesis and production of rice on a short-term, but the long-term effects of elevated [CO_2] on the quality and quantity of rice production is yet to be resolved and need some attention with respect to various environmental constraints.

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Keywords

Climate change · CO_2 · Elevated concentration · Enriched · Fumigation type · Mitigation · Open chamber · Rice production · Temperature

Abbreviations

C	Carbon
$[CO_2]$	Atmospheric carbon dioxide concentration
CH_4	Methane
FACE	Free-air CO_2 enrichment
FAO	Food and Agricultural Organization
IPCC	Intergovernmental Panel on Climate Change
LAI	Leaf area index
N	Nitrogen
O_3	Ozone
P	Phosphorus
PPM	Parts per millions
RuBisCO	Ribulose-1,5-bisphosphate carboxylase

17.1 Introduction

More than half of the world population is dependent on rice (*Oryza sativa* L.) as a staple food source (Coates 2011; De Costa et al. 2003; IRRI 2002; Tuong and Bouman 2003). The production of rice is globally distributed which encompasses many countries over varied range of conditions between 45°N and 40°S latitude embracing Central America, Southern half of the USA, most of South America, Africa, Australia, India, China, Japan, the Philippines, and Southeast Asia (Bouman et al. 2002, 2007; De Costa et al. 2003; Dari et al. 2017; Sihi et al. 2017; Welch et al. 2010). Rice being highly produced and consumed in Asia (FAO 2013) is expected to increase its demand by about 30% by 2050 (Alexandratos and Bruinsma 2012). Among all other cereal crops, rice must be produced on a larger scale to mitigate the higher caloric intake of growing population. No matter what one's political persuasion about all environmental policies to control CO_2 emissions, it is well known that the concentrations of atmospheric CO_2 $[CO_2]$ have been risen from about 280 to >400 ppm since 1800 (World Meteorological Organization (WMO) 2017) and anticipated to rise to the level of 500–1000 ppm at the end of this century (Houghton 1996). Concurrently, the unintended benefits of enriched $[CO_2]$ in the atmosphere could possibly and positively contribute toward meeting the demand of higher production of rice in the face of climate change.

Photosynthesis being the prime physiological process in plant production and productivity for any agricultural crops and the CO_2 being a fundamental substrate for photosynthesis, it is crucial to quantify the plant physiological processes in terms of crop production and productivity under elevated CO_2 concentration in the atmosphere. The change in the concentrations CO_2 might be responsible for the change in global radiation fluxes, thus the global climate change since CO_2 is an important 'greenhouse gas' which is transparent to visible light but it absorbs strongly at infrared light. The scientists throughout the world are debating about the global temperatures and precipitation which will increase by 1.4–5.8 °C and 5–20%, respectively, during the current century. Therefore, it is anticipated that increasing concentration of CO_2 and global climate change will certainly impact the plant community (Patindol et al. 2015). The impact in plant communities can be both positive and negative under elevated CO_2 concentration; thus the future of food quantity and quality might be dwindling.

Common consensuses among global climate chnage includes a projected increase of 21°C in global temperature can nullify the positive effect of elevated [CO_2] in rice production and productivity, as well as enhanced water shortage in combination with increasing temperature, will restrict the rice production substantially as modeled by CERES rice model in Northern India (Lal et al. 1998). As, for example, on an average, a 23% increase in rice yield has been reported with an increase in elevated [CO_2] (~627 ppm) (Patindol et al. 2015); thus it reporting the impact of enriched [CO_2] on rice production and productivity under changing global climate given increasing India's population will be noteworthy. Here, we review the perspective of the direct and interactive effect of different environmental factors (such as temperature, ozone, genotype/variety, etc.) and enriched CO_2 concentration on the production and productivity of rice. This chapter will end up with some mitigation or adaptation strategies for elevated CO_2 production with respect to rice production and productivity.

17.2 Rice Production and Elevated [CO_2]

Decadal studies are conducted to realize the response of rice crops under expected elevated [CO_2] environment, and global warming showed mixed results with some positive and some negative effects (Ziska and Teramura 1992; Kim et al. 2001; Peng et al. 2004; Ziska et al. 2012). Data obtained from variable sources showed a variable positive yield increase in rice under enriched [CO_2] (Table 17.1) which ranged from 11 to 71%. Therefore, an increase in the atmospheric [CO_2] would lead to a positive or negative yield increase in any agricultural crops including rice which depends on the type of the photosynthesis occurring in that particular plant system either the plant is C_3 or C_4. The process of carbon fixation (conversion of atmospheric CO_2 into photosynthetic plant product, i.e., glucose) is varied among various crops.

To that end, the ribulose-1,5-bisphosphate carboxylase (RuBisCO) is a crucial enzyme for carbon (C) fixation in any C_3 and C_4 plant systems. However, this conversion process operates differently in these two types of plant communities under changing atmospheric [CO_2] with global climate. As, for example, the net photosynthetic CO_2 uptake is generally enhanced in C_3 crops under enriched [CO_2]

Table 17.1 Effects of elevated carbon dioxide concentration in yield and production of rice

Level of elevated [CO_2] (unit)	Rice production or yield (%)	References
627 ppm	23	Ainsworth (2008)
610 ppm	71	Bloom (2006)
530μmolmol^{-1}	19	Kimball (1983)
540μmolmol^{-1}	11	Cure and Acock (1986)
610μmolmol^{-1}	12	Long (2006)

since the presence of RuBisCO inhibits the competing oxygenation reaction leading to photorespiration; thus the RuBisCO is not CO_2 saturated in today's atmosphere. The effects of increased atmospheric [CO_2] could be more pronounced over terrestrial C_3 plants such as rice, wheat, etc. as a prompt response to photosynthesis. It has been reported that a positive change of 38% in photosynthetic rate might be possible in C3 plants at 25 °C if the atmospheric [CO_2] changed from 400 to 550 ppm as projected by 2050. Conversely, the photosynthetic process in C_4 crops such as maize and sorghum remains comparatively unchanged or relatively less affected as these enzymes are situated in bundle sheath cells where the CO_2 is concentrated as high as three to six times than atmospheric [CO_2]. This is why C_4 crop yield generally remains unaltered by elevated [CO_2]. However, a recent study reported a reversal in this C_3-C_4 paradigm under a long-term (two decades) elevated CO_2 treatment (Reich et al. 2018). Irrespective of whether a C_3 vs. C_4 crops show a direct response to photosynthetic activity, an indirect increase in the efficiency of water use via a reduction in stomatal conductance may still increase yield.

17.3 Various Approaches: Scenarios of Rice Production Under Elevated [CO_2]

Many researchers have attempted to mimic the future climate change scenarios with enriched [CO_2] by creating various ambiances for future rice crops. Among many such approaches, the commonly used system of rice production under elevated [CO_2] involves growing rice crops under open top chambers; production of rice plants in growth chambers, i.e., under controlled environments; rice grown in the field using the free-air CO_2 enrichment (FACE) condition; or rice crop production in a temperature gradient tunnels. Among all these, the free-air CO_2 enrichment systems have been identified to be the most efficient system of production of rice under enriched atmospheric [CO_2] which provides a natural environment for rice crops (Fig. 17.1).

In general, approximately 12% increase in yield of rice and other growth determining factors such as panicle numbers, biomass, grain numbers, harvest index, leaf area index (LAI), total leaf N content, etc. has been reported under the experimental approach named as free-air CO_2 enrichment system (Fig. 17.2). It has been reported that kernel amylose content of rice increased due to elevated [CO_2] (~ from 350 to 700 ppm) in combination with increased phosphate fertilization in growth chamber

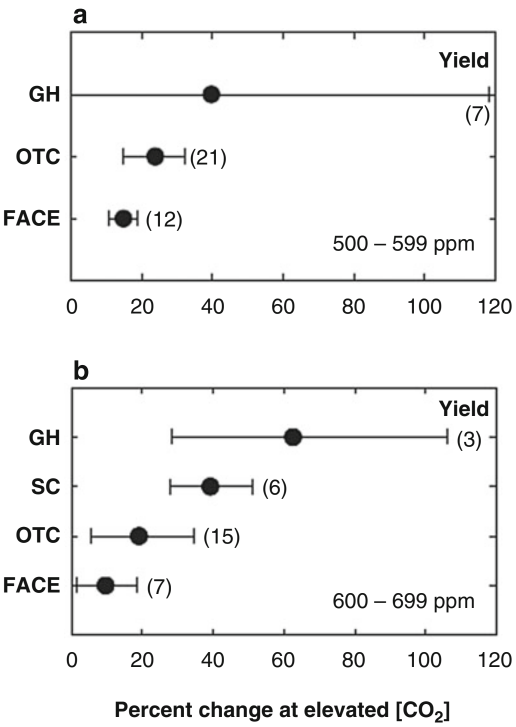

Fig. 17.1 The representation of rice yield at reduced (upper panel) and increased (lower panel) concentration of CO_2. (Adapted from Ainsworth 2008)

experiments (Seneweera et al. 1996). Conversely, the grain amylose content and other factors of rice grain quality tested by sensory evaluation usually reduced under CO_2 enrichment in the free-air CO_2 enrichment systems (Terao et al. 2005). Additionally, other experiments under the free-air CO_2 enrichment systems with different rates of N fertilizer application reduced the amylose content but reasonably increased the rice yield, paste viscosity, and chalkiness (Yang et al. 2007).

17.4 Factors Impacting Rice Production Under Elevated [CO_2]

17.4.1 Effects of CO_2, Temperature, and Their Interactions

The growing seasons are usually shortened due to increased temperature which affects the rice yield adversely, but elevated [CO_2] has the exact opposite effects (Erda et al. 2005). The change in atmospheric [CO_2] has noticeably affected the relationship between various biochemical pathways in plants systems for carbon metabolism and the production of amino acids from inorganic nitrogen (N). Therefore, the yield variation in rice can greatly be explained by this interaction with respect to elevated CO_2 concentrations. One of the most common research areas in this aspect is to study the combined study of both elevated [CO_2] and atmospheric

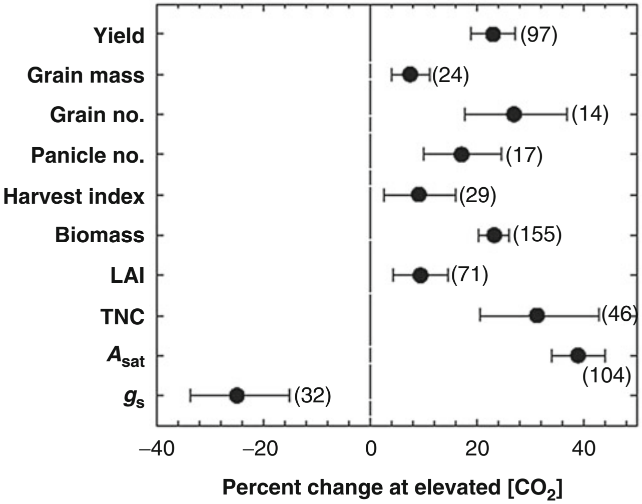

Fig. 17.2 The growth and growth determinant factors of rice crops under elevated CO_2. The horizontal lines surrounding each parameter represent 95% confidence interval values. The values in the parentheses are the degrees of freedom. *LAI* leaf area index, *TNC* total leaf nonstructural carbohydrates, A_{sat} light-saturated photosynthetic rate, g_s stomatal conductance to water vapor. (Adapted from Ainsworth 2008)

temperature change under rice production system. It is important to note in this context that although the increase in global temperature (~1.1 to 6.41 °C) can elevate the atmospheric [CO_2], it depends on the global emission scenarios (Meehl et al. 2007). While warming (2–4 °C) will decrease yield, the combination of warming and elevated [CO_2] compensate the increase in the rice production and productivity as a result of the enhanced concentration of atmospheric CO_2. The better grain quality has been reported to maintain by more heat-tolerant rice cultivars than standard cultivars under enhanced [CO_2] (Usui et al. 2014). On the other hand, a decrease in amylose and protein contents, as well as unchanged total starch and caloric energy values in rice, has been showed with an increase in atmospheric concentration of CO_2 (Goufo and Trindade 2014).

17.4.2 Effects of Interaction Between CO_2 and Ozone (O_3)

The effects of the concentration of atmospheric O_3 on growth, production, and productivity of various crops including rice are well reported. In general, the elevated concentration of CO_2 negates the adverse effects of O_3. Therefore, the interaction between elevated [CO_2] and elevated [O_3] in the atmosphere and its responses to rice production and productivity are important under enriched [CO_2] environment. In general, the rise in atmospheric [CO_2] is closely related to an increase in tropospheric O_3 and temperature. A 14% yield reduction including significant adverse effects on other growth determinants such as grain quality (number and/or mass), photosynthetic rate, and index for leaf area (LAI) have been reported in rice grown with an exposure of 62 ppb O_3 (Ainsworth 2008). A mixed report on the CO_2-induced yield increase was explained by Reid and Fiscus (2008), while they conducted an experiment in a controlled ambient (fixed concentration of CO_2), i.e., air filtered by charcoal, suggesting other potential resource limitations. However, a modification in enriched concertation of CO_2 has also been reported by the normal atmospheric concentration of O_3 which can be considered as a resource-limited system under experimental approach, thus signifying the consideration of better management of resources for future rice crop production under elevated [CO_2].

17.4.3 Effects of Interaction Between CO_2 and Other Elements (Nitrogen and Phosphorus)

In general, the quantity and availability of N among all other plant nutrients determine the production and productivity of any crops including rice. Other than that, among other environmental factors, the availability of N to crop plants is the most discussed factor which can be affected by the increased concentration of atmospheric CO_2 (Anten et al. 2004). Therefore, the response of rice in terms of production and yield is generally more pronounced under the enriched concentration of CO_2 in an open top chamber as compared to pots due to more availability of N in fertilized pots compared to the natural soils.

The combination of availability of N and enriched concentration of atmospheric CO_2 has influential impact on plant infrastructure, LAI, and canopy photosynthesis (Fig. 17.3; Anten et al. 2004). Rice grown at an enriched atmospheric concentration of CO_2 (~200 pmol mol^{-1} using the FACE approach) and at higher N-enriched conditions in FACE had a higher light-saturated rate of photosynthesis which results in an apparent higher quantity of rice yields than rice plants grown in ambient conditions. It has also been reported that the LAI has increased strongly in relation to the N availability. A prominent interaction between N and CO_2 on canopy carbon gain, growth, and yield of rice crops can be explained by a strong relationship between leaf N and elevated concentration of CO_2 in comparison to a normal atmospheric concentration of $CO_{2.}$ It is highly possible that enriched concentration of CO_2 and plant N availability enhance the LAI, thus, positive yield responses.

Another important factor other than N, which impacts the rice production under enriched concertation of CO_2, is the management of P which has explicitly been mentioned by Yang et al. (2007). The elevated [CO_2] has significant effects on the ratio of the shoot to root P uptake which is usually modified by seasonal changes and acquired at grain maturity. In free-air CO_2 enrichment approach, the shoot P uptake by rice crop under enriched [CO_2] environment declined gradually with crop development as compared to ambient condition (Yang et al. 2007). Additionally, P use efficiency for biomass throughout the growing season and grain yield and P

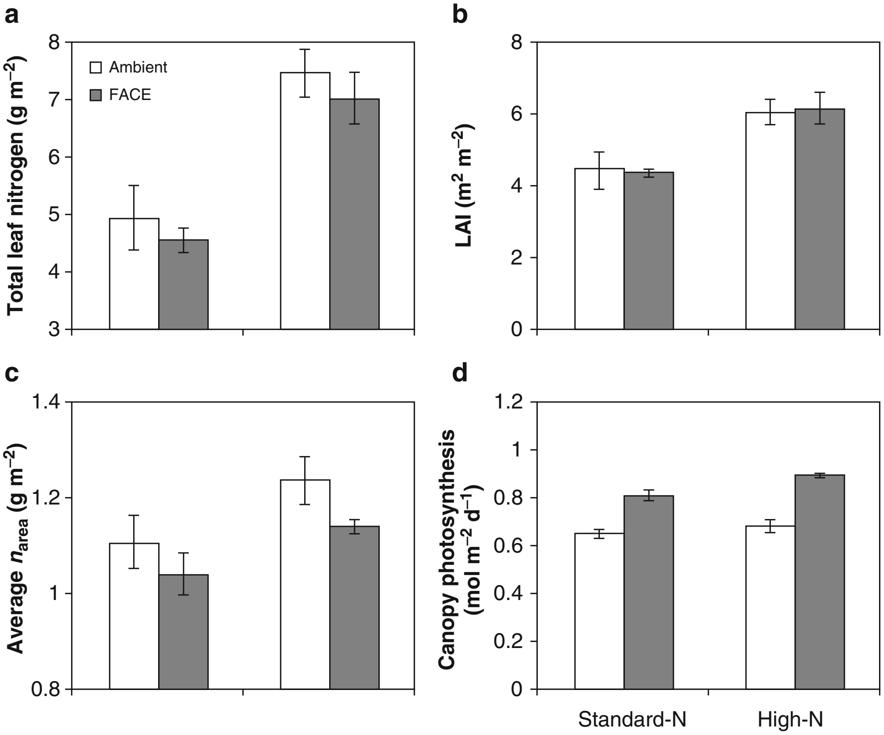

Fig. 17.3 (**a**) The total leaf nitrogen, (**b**) leaf area index, (**c**) average N content per unit leaf area (n_{area}), (**d**) canopy net daily photosynthesis of rice (*Oryza sativa*) grown in either ambient or FACE experiment. (Adapted from Anten et al. 2004)

harvest index at grain maturity significantly decreased in the FACE when compared to ambient-type climate change studies.

17.4.4 Effects of Other Environmental Factors

In general, the decreased moisture has reduced the effect on rice production under elevated [CO_2]. It is relatively important to report the effect of water use by rice under the elevated [CO_2]. However, the exact prediction of the rice yield by calculating accurate water use by plants under future climate change is almost impossible although scanty of information on the diurnal and seasonal variation in stomatal conductance of under enriched concentration of CO_2 is available (Shimono et al. 2010). Experiments with various cultivars proved to decrease the stomatal conductance of rice crops by approximately 64% over a period of 2 years with a general higher conductance in day time (morning plus noon) as compared to the afternoon under enriched concentration of CO_2. Other factors such as genotype and environmental factors might greatly affect responses of rice yield under elevated concentration of CO_2.

17.5 Effects of Elevated [CO_2] on Food Quality

The grain/food quality is the most important aspect of rice production, while discussing the rice yield under elevated or enriched [CO_2] environment given climate change is happening. The importance of giving more emphasis on the future food supply rather than criticizing various methodologies by characterizing the uncertainties related to biotic and/or abiotic stress management under scenarios of the enriched concentration of atmospheric CO_2 has been realized (Ziska et al. 2012). The protein content is one of the most important characteristics while considering the rice food quality. Terao and his co-workers (2005) have shown that rice grown under ambient conditions produce a significantly lower quantity of protein as compared to rice grown under enriched [CO_2]. Improvement of other associated but essential characteristics in rice grain quality includes either enhanced whiteness of the rice grains and/or viscosity or decrease the surface hardness and/or unaltered amylose content. In contrast, other sensory properties of rice (e.g., appearance, aroma, deliciousness, and palatability index) have been reported being unaltered by a change in atmospheric CO_2 concentration (Terao et al. 2005).

Growth and N allocation of tropical rice have been modified because of CO_2 fertilization and elevated nighttime temperature. Rice crops grown on elevated [CO_2] (550 lmol mol^{-1})/enriched C fertilization for 3 years in field showed significantly increased biomass production (both above ground and below ground), grain quality, and stoichiometry of mineral nutrients such as C and N in various plant parts (Fig. 17.4) than that of ambient CO_2 in control chamber-grown rice (Roy et al. 2015). In general, the grain yield of rice significantly increased (20–30%) under elevated [CO_2] compared to control chamber situation. It has been reported that the introduction of more heat-tolerant rice cultivars will improve the overall rice grain quality at elevated [CO_2] than under normal level (Usui et al. 2014). An additional factor which might affect the grain quality along with elevated [CO_2] is heat stress because elevated [CO_2] will likely lower the threshold temperature for heat stress. The enriched concentration of CO_2 has also been reported to directly inhibit the rice canopy respiration over a varied range of short-term air temperature treatments (Baker et al. 1992). The effect of ground area basis canopy respiration (Rd) under elevated [CO_2] at air temperature above 21 °C can greatly impact the rice grain quality with diurnal variation in CO_2 concentration, e.g., 350 $\mu molmol^{-1}$ vs. 700 $\mu molmol^{-1}$, during the daytime.

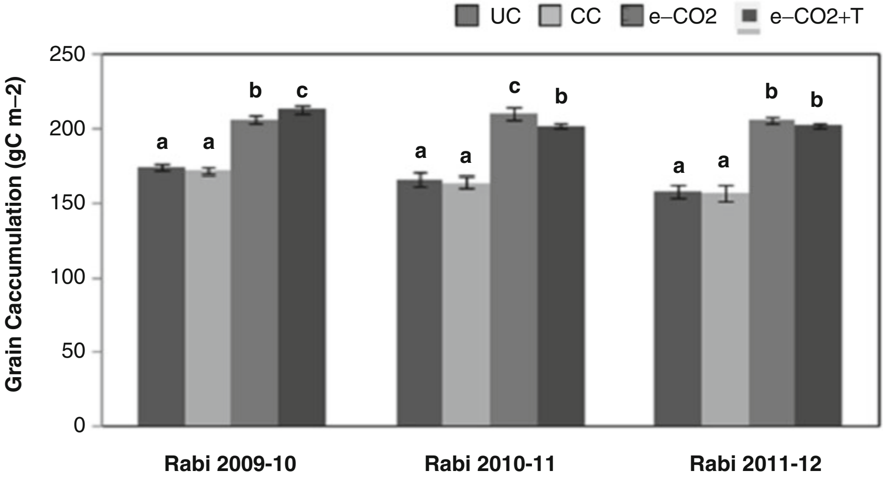

Fig. 17.4 Grain carbon accumulations under four growing conditions such as unchambered ambient CO_2 (UC), chambered ambient CO_2 (CC), elevated CO_2 (e-CO_2), and elevated CO_2 + elevated temperature (e-CO2 + T) over three Rabi (winter) cropping seasons. The columns followed by a common letter in a particular growth stage do not significantly ($p < 0.05$) differ by Tukey-Kramer's HSD test. (Adapted from Roy et al. 2015)

17.6 Mitigation and/or Adaptation

The production and productivity of rice crops under elevated [CO_2] in the face of climate change are invincible. Therefore, research approaches are followed by the various conditions to either mitigate or adapt the future of rice production under elevated [CO_2]. However, the responses might vary depending on the experimental technique (either lab-oriented or field-based) used to grow rice under elevated [CO_2] conditions. For instances, a special traits in rice cultivars i.e., kernel chalkiness, which is considered a a very common visual environment-related stress, could be modified by some environment interactions such as temperature (Patindol et al. 2014). Therefore, fumigation-type situation to grow rice which will approximate the field condition would be one possible way the mitigation or adaptation strategies to combat the climate change and secure substantial production of rice.

Identification of high heat-tolerant germplasm for rice crops can effectively negate the adverse effect of high temperature on elevated [CO_2] of climate change to compensate the change in production or yield future rice crops. Another aspect of mitigation would be to utilize environmental tolerant rice varieties having some specific traits in a gene which is more resilient to change under the enriched concentration of CO_2 and adverse environmental conditions. As, for example, the kernel chalkiness, a very common visual environment-related stress, could be modified by some environment interactions such as temperature (Patindol et al. 2014). Consequently, identification of genotypes and their interaction with related environmental factors under variable temperature and/or enriched [CO_2] in various locations would be a possible attempt at mitigation/adaptation.

17.7 Conclusions

The production, productivity, and calorie intake of rice among all other cereal crops in the South Asian countries but mainly in India are of great significance in global food market/business. It is well known that the Intergovernmental Panel on Climate Change (IPCC) has estimated an increase of the elevated concentration of CO_2 which will impact the future of rice production and productivity. Climate change (increased air temperature) being the main culprit to this elevated [CO_2]. Thereafter, the interrelated influence of both [CO_2] and air temperature along with other environmental or crop-related factors has a tremendous impact on rice production (Fig. 17.5). Results from both laboratory- and field-based experiments on elevated [CO_2] and increased air temperature showed positive and negative effects on rice crop yield, respectively. However, their combined effects explicitly describe different scenarios, e.g., the increased effect of elevated concentration of CO_2 in rice production and productivity can be nullified by the effect of increased temperature in the atmosphere. Investigations were made to explain the responses of the enriched concentration of CO_2 on production and productivity of rice under various controlled environments among which the free-air controlled experiment (FACE) systems have been identified to be the most efficient system of rice crop production

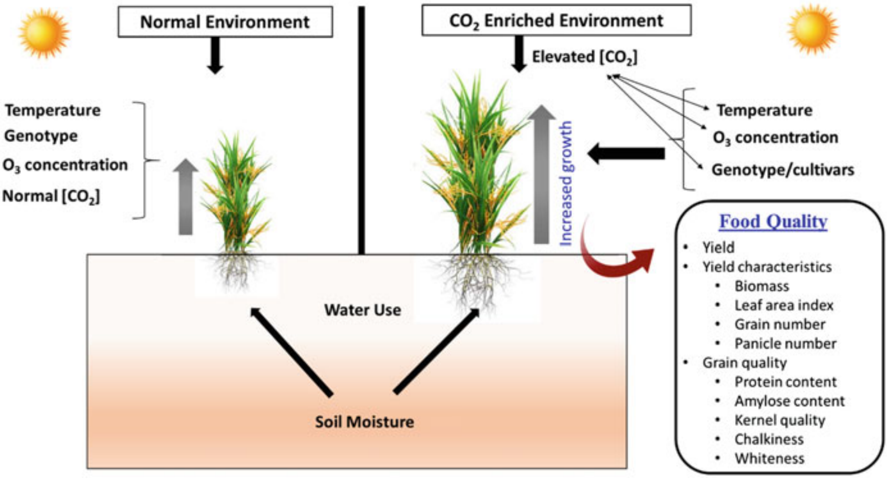

Fig. 17.5 Schematic diagram of future rice crop production under elevated/enriched CO_2 environment. The combination of various environmental factors such as temperature, ozone, CO_2 concentration, or plant parameters such as genotype or cultivars under elevated or enriched CO_2 environment compared to normal environment promoted the rice growth, yield, and food quality. [CO_2] concentration of CO_2, O_3 ozone

under elevated [CO_2] which provides a natural environment for rice crops. However, the findings of rice production and productivity under elevated [CO_2] in these experimental approaches are quite mixed and inconsistent. It is noteworthy to mention that the overall growth, production, and productivity of rice crops have been enhanced due to short-term stimulation of photosynthesis under the elevated concentration of CO_2 (Fig. 17.5). However, the long-term scenarios of rice production and yield in the current situation of global climate modifications under real field situation should be discussed more in details with all pros and cons.

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