Role of Microbes in Climate Smart Agriculture

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Abstract

Impact of climate change on agriculture and food production is already perceptible. In the present scenario of rising temperature, changing patterns of rain; increasing occurrence of extreme climatic events such as cyclone, drought and flood; the concept of climate smart agriculture (CSA) originated in order to make agriculture more resilient to climate change. Sustainably enhancing efficiency, adaptation to and mitigation of climate change are three pillars of CSA. Microorganisms are vital to several ecological processes in agroecosystem such as organic matter decomposition, nutrient cycling, N_2 fixation, phosphate solubilization, nutrient acquisition and recently discovered probiotics role. Appropriate management and exploitation of beneficial microbial functions such as use of biofertilizer, biopesticide, plant growth-promoting rhizobacteria, etc. help in achieving sustainable goal and alleviating adverse impact on environment. Microorganism can be used to facilitate adaptation to climate change by promoting growth and development and imparting resistance against several abiotic stresses. Soil microbes and their metabolic activity can influence land–atmosphere carbon exchanges in numerous ways, while these can be broadly divided into different groups as those that affect the ecosystem by methane and carbon dioxide uptake and that also control carbon loss from the soil through methane production and respiration. The role of microbe as a source and sink of greenhouse gas can be exploited to devise mitigation strategy for climate change.

Keywords

Climate smart agriculture · Rhizobacteria · Agroecosystem · Methane greenhouse gas · Mitigation

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7.1 Introduction

Several scientific evidences show that the climate system is warming, and according to climate model projections during the twenty-first century, the global surface temperature is likely to rise further 0.3–1.7 °C in the lowest and 2.6–4.8 °C in highest emission scenario. Many of the unprecedented extreme climatic events taking place since 1950 point towards global climate change phenomenon. Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report concluded that human influence has been the dominant cause of the prevailing phenomenon of global warming and climate change.

Worldwide, agriculture both contributes to and is threatened by climate change. The report of the IPCC indicates that agriculture contributes about 47 and 58% of total anthropogenic emissions of methane (CH_4) and nitrous oxide (N_2O), respectively. Climate change has already drastic impact on agriculture (Lobell et al. 2011) and is further going to impact directly and indirectly food production. Increase of mean temperature, changing patterns of rain and increasing frequency of extreme climatic events like cyclone, drought and flood will have profound impacts on agriculture (IPCC 2007).

The world's population is predicted to increase by one-third by 2050, and most of the additional two billion people will live in developing countries (FAO 2009). In order to meet the expected demand for food and feed, it has been estimated that the agricultural production will have to increase by 60%. Confronting food security challenges are huge because resources needed for sustaining or improving current production level already being threatened. Moreover, climate change is already negatively impacting on agricultural production worldwide and locally, and climate risks to cropping, livestock and fisheries are expected to increase in the coming decades. Transformation and reorientation of agricultural production under the new realities of climate change gave rise to concept of climate smart agriculture (CSA). According to the definition of Food and Agricultural Organization (FAO) of the United Nations, CSA is an integrative approach of agricultural production that aims at sustainably increasing efficiency, enhancing adaptation with mitigating GHG emission where possible and enhancing achievement of national food security goal.

Microorganisms are the most important components of agricultural ecosystem for which without them agriculture and food production simply could not exist. Microorganism plays essential functions in plant nutrient cycling in soil–plant–microbe–atmosphere continuum. Microbes are key components of carbon and nitrogen cycles and responsible for both the production and consumption of greenhouse gases such as carbon dioxide, methane and nitrous oxide. The large diversity of microbes provides an untapped opportunity of improving efficiency of agricultural production, adapting to and mitigating climate change effects, thus achieving goals of climate smart agriculture. Microorganisms that are disease causal organisms for weeds and insect pests can be used as biopesticides. Many beneficial plant–microbes are associated in the soil where they encourage for resistance or perform biological control functions. Soilborne free-living microorganisms contribute to the formation and building of the structure of soil, simultaneously the storage of nutrients and sequestration of carbon. However, some microbes acting in association with crop plants further regulate soil fertility and accessibility of nutrients. Soil microorganisms are also liable for bioremediation in the polluted sites by restoring soil fertility.

7.2 Microbial Functions in Agroecosystem

Microbial diversity in soil catalyse umpteen number of processes that are integral components of biogeochemical cycles and hence support several agroecosystem functions such as organic matter decomposition, availability of nutrient and overall soil and plant productivity. Microbes often form consortia and supply different limiting resources to plants. In addition to this presence of plant-specific microbe, e.g., N_2 fixers and mycorrhiza apart from enriching soil with specific nutrient also help the plants to acquire limiting nutrient required for their growth and production. As a result microbes promote agroecosystem functioning and sustainability and agricultural system.

7.2.1 Organic Matter Decomposition and Nutrient Cycling

The breakdown of complex organic molecules of dead material into simpler organic and inorganic molecules with biochemical transformation is known as biological process of decomposition (Juma 1998). In recycling energy and plant nutrients, microorganisms break down the organic matter, and any excess nutrients (N, P and S) are released into the soil in forms that plants can use properly; the release process is called mineralization. Therefore, microorganisms play an important role in nutrient cycling processes in soil with organic nutrients and some inorganic compounds that are supplied through exudation by plant roots and animal excreta and death of plants and animals.

7.2.2 N_2 Fixation (Nitrogen Fixation)

Nitrogen fixation is one of most crucial beneficial biological processes for the environmental sustainability of agriculture worldwide. Globally, the annual inputs of fixed nitrogen in form of crop legume–rhizobia symbioses are estimated to be 2.95 million tonnes and 18.5 million tonnes for pulses and oilseed legumes respectively (Howieson et al. 2005). However, legume plants and root-nodulating bacteria with their symbiotic associations belonging to the genera *Rhizobium*, *Mesorhizobium*, *Bradyrhizobium* and *Ensifer* produce around 80% of nitrogen in grains, with maximum profit each year. Some examples of free-living nitrogen-fixing organisms are as follows: *Azospirillum*, commonly connected with cereals in temperate zones; Beijerinckia, seems to be associated with sugar cane plantations in the tropical zones; and Azotobacter, plays an important role in nitrogen fixation in rice crops and also is used as biofertilizer for wheat, maize, barley, oat, sunflowers, line, beetroot, coconuts, coffee, tea and tobacco. However, some species belonging to the genera *Azospirillum*, *Herbaspirillum* and *Gluconacetobacter* are sugarcane endophytes and supply to its nitrogen fertilization. Nitrogen-fixing *Azorhizobium* strains have been isolated from wheat roots whereas *Rhizobium* and *Bradyrhizobium* from rice roots. Moreover, certain diazotrophic bacteria set up a truly mutualistic symbiosis with few plants through the formation of root nodules (García-Fraile et al. 2015).

7.2.3 Phosphate Solubilization

Phosphorus solubilizing microorganisms (PSMs) plays a vital role in phosphorus nutrition by enhancing the accessibility of P to plants through the release of organic and inorganic soil phosphorus pools by mineralization and solubilization (Walpola and MinHo 2012; Sharma et al. 2013). A diverse group of bacteria (*Pseudomonas*, *Bacillus*, actinomycetes) and fungi (*Aspergillus*, *Penicillium* species) are capable of solubilizing and mineralizing plant available forms of phosphorus in the soils, and its benefits from their use as inoculants are increasingly being recognized, especially in P-limited environments (Gyaneshwar et al. 2002). Bacteria are observed to be more effective than fungi in phosphorous solubilization (Sharma et al. 2013). *Penicillium bilaii* is another beneficial microflora which helps to unlock phosphate from the native soil. Fungus is thought to turn out an organic acid that dissolves the phosphate in soil so that plant roots can easily utilize it. Among soil bacterial groups, *Rhizobium*, ectorhizospheric strains of *Bacilli* and *Pseudomonas*, *Enterobacter* and endosymbiotic rhizobia are recorded as effective strains of phosphate solubilizers (Khan et al. 2009).

7.2.4 Nutrient Acquisition Through Mycorrhizal Symbiosis

Mycorrhizal symbiosis involves reciprocal transfer of carbon and nutrients between host plant and mycorrhizal fungus (arbuscular mycorrhizal fungi, AMF). The fungus provides the host plant with nutrients, i.e. nitrogen and phosphate, which increase resistance of the host to biotic and abiotic stress and in return plant transfers between 4–20% of the photosynthetically fixed carbon to mycorrhizal fungus. Although AMF symbiosis is widespread, its symbiotic functions differ from species to AMF isolates, host plants and soil properties. Arbuscular mycorrhizal fungi associations are generally considered to be diffuse and non-specific because of their multiple species colonization linking together two or more plants (Selosse Marc-Andre et al. 2006). Arbuscular mycorrhizal fungi symbiosis is one of the key beneficial biological processes for the treatment of contaminated soils and mining sites (Smith et al. 2008).

7.2.5 Probiotics Role of Microbial Community

Probiotics are the microorganisms that are thought to provide health benefits when consumed. Probiotics concept has been given by the Nobel laureate Élie Metchnikoff who suggested that dependence of the intestinal microbes on food makes it achievable to adopt measures to modify the flora in our bodies and to replace the harmful microbes by useful microbes. Soil probiotics are commonly considered as soil-based organisms (SBOs) because they are beneficial bacteria that live in soil. Plants have a limited capability to genetically adapt to rapid change in the environment, i.e. toxins, limited nutrients and drought, for which they might use microbes to have capacity to rapidly progress in the changing atmosphere at shorter life cycles. This is how plant mechanism shows a similar trend as of humans taking probiotics to improve health. Plant-specific stimulation of specific microbial groups in their rhizosphere zone suggests that plants might have evolved to tactically stimulate and support particular microbial groups which are capable of producing antibiotics as a defence against diseases caused by soilborne pathogens (Weller et al. 2002). Soil bacteria belonging to genus *Pseudomonas* are ubiquitous in most soils and have been linked to wide-ranging processes including nutrient cycling, plant growth promotion and inhibition, disease control, nitrogen fixation and bioremediation. Pseudomonads act as biocontrol potential against fungi and oomycete pathogens for more than two decades (deSouza 2002). Antibiosis is the most commonly suggested trait responsible for their activity against the plant pathogens, and a number of antimicrobial compounds have been identified, for example, 2,4-diacetylphloroglucinol (2,4-DAPG), phenazines, pyrrolnitrin, pyoluteorin, hydrogen cyanide and biosurfactant antibiotics (Picard et al. 2008). Their ability to respond quickly to changes in physical, chemical, carbon and nutritional conditions in the soil has been associated to their functional importance in agricultural ecosystems.

7.3 Role of Microbes in Sustainable Agriculture

Sustainable agriculture is that type of agriculture which focuses on producing long-term crops and livestock while having the minimal effects on environment. Such type of agriculture tries to find a good balance between the need for food production and preservation of the ecological system within the environment. One of the important criteria for ensuring sustainable agriculture is maintaining the quality of the soil of which microbes are integral part. The critical milestones of achieving sustainability are devising efficient nutrient recycling strategy, pest and disease control methods and minimizing negative effects of abiotic stress. Most of these activities are mediated by microbial services; hence appropriate management and exploitation of beneficial microbial functions can help in achieving sustainable goal and alleviating adverse impact on environment. Major impact of agricultural microbiology on sustainable agriculture would be to replacement and/or integration of agrochemicals (mineral fertilizers, pesticides) with the microbial preparations. Some of wide explanations on the use of microbes in sustainable agriculture are biofertilizer, biopesticide, and plant growth-promoting rhizobacteria (PGPR).

7.3.1 Biofertilizers

Biofertilizers are one of the best tools for sustainable agriculture which is a gift to the modern agricultural science. Biofertilizer is being applied in the agricultural field as a substitute to the organic manure. Organic manure-consisting compost, i.e. household wastes, a green manure and farm yard manure, may maintain the quality and sustainability of soil in the long run but not be able to meet the immediate requirement of crop. At the same time, chemical fertilizers have their own impact on environment in terms of fossil fuel burning, greenhouse gas emission and soil, water and air pollution. In addition to this, continuous use of chemical fertilizer alone causes nutrient imbalance in soil affecting its sustainability. Biofertilizer contains microorganisms which promote adequate supply of nutrients to the host plants and ensure proper improvement of growth and regulation in their physiology. Living microorganisms are used in the preparation of biofertilizers which have specific functions to enhance the plant growth and reproduction. Biofertilizer being a crucial component of organic farming plays a vital role in maintaining sustainability and long-term soil fertility. Some microorganisms which can absorb gaseous nitrogen directly from atmosphere and make it accessible to the plants can be identified and then multiplied in laboratories and introduced into the root zone of crop plants to supply nitrogen. Materials containing such organisms or plants are called biofertilizers. Some commonly used biofertilizer in agriculture are *Rhizobium*, *Azotobacter*, *Azospirillum* blue-green algae, *Azolla*, etc.

7.3.2 Biopesticide

Biopesticides are derived from natural materials such as plants and bacteria and contain minerals broadly used for controlling insects and disease-causing pathogens. They are broadly categorized as microbial pesticides, plant-included-protectants and biochemical pesticides that are produced through naturally occurring substances which control pests by harmless mechanisms. Microbial insecticide like *Bacillus thuringiensis* (*Bt*) produces toxin a which paralyse the mid gut of insect pest and prevent further feeding. Similarly spores of *Beauveria bassiana* and *Metarhizium anisopliae* penetrate the host cuticle and produce toxic metabolites known as beauvericin and destruxins, respectively, which cause death of the insects. Since biopesticides are inherently less toxic, affect only the target pest, are easily biodegradable and are effective in small quantities, they cause lower exposure and avoid pollution problems in the environment.

7.3.3 Plant Growth-Promoting Rhizobacteria (PGPR)

Plant growth-promoting rhizobacteria (PGPR) are some of the naturally occurring soil bacteria which have the ability to benefit plants by improving their immunity and productivity. However, these bacteria are associated with rhizosphere and some part of soil under the control of plant roots and their exudates. Due to their interactions with plants, PGPR can be separated into symbiotic bacteria (live inside the plants and exchange metabolites directly) and free-living rhizobacteria (live outside plant cells) (Gray and Smith 2005). Moreover, some of symbiotic bacteria have the ability to integrate their physiology with plant, resulting in formation of specific structures. In accordance with their mode of action, PGPR is being classified as biofertilizers, biopesticides and phytostimulators with certain bacteria having overlapping applications. The attachment of ACC (1-Aminocyclopropane-1-Carboxylate) deaminase gene and the presence of phytohormones like IAA (Indole Acetic Acid), siderophore, cytokinin, gibberellins, etc. seem to be responsible for enhancing the plant growth and yield and the nutrient uptake from various crop plants in different agroecosystems. According to research, the diversity of PGPR application can be used as a reliable component in the management of sustainable agricultural system.

However, selection of the best rhizobacterial strain for rhizosphere capability and making a good study on the ecology of introduced PGPR with the inhabitant PGPR and other microbial species in the plant rhizosphere will require a more widespread knowledge.

7.4 Microbial Contribution to Climate Change

Emission of some potent greenhouse gases responsible for global warming such as CH_4, N_2O and Carbon dioxide (CO_2) is essentially a by-product of microbial processes. Microorganisms are integral components of C–N cycle in soil; they break down organic matter and release carbon dioxide back into the atmosphere. Microbial respiration is an integral component of soil respiration which is a major pathway of carbon efflux from ecosystem and accounts for 25% of naturally emitted CO_2. Similarly a group of bacteria called methanogens are responsible for production of CH_4, another important greenhouse gas having global warming potential 25 times more than that of CO_2.

Natural emissions of N_2O primarily result from bacterial breakdown of nitrogen in soils and in the earth’s oceans. In soils nitrous oxide is produced as a by-product of both denitrification and nitrification processes which are carried out by group of microorganisms known as denitrifiers and nitrifiers, respectively. Nitrification is the main source of N_2O under aerobic conditions, while denitrification dominates in anoxic environment. Denitrification is the microbial reduction of nitrate or nitrite form of N to dinitrogen or N oxides under anaerobic condition. Nitrification is the process of oxidation of ammonium form of N to nitrite or nitrate form and also responsible for the emission of N_2O from soil. In aerobic conditions, nitrifier nitrification involving ammonia oxidation by autotrophic ammonia-oxidizing bacteria is the major pathway of N_2O formation. Anaerobic ammonium oxidation (ANAMMOX) is an alternate microbial-mediated pathway responsible for N loss in the form of N_2 and N_2O in aquatic system. The global warming potential of nitrous oxide is 298 times more than the CO_2, and it accounts for about 19% of total global warming effect. Globally soils covered by natural vegetation are estimated to produce 6.6 Tg of N_2O annually, and oceans are thought to add around 3.8 Tg of N_2O annually to the atmosphere.

7.5 Microbial Response to Climate Change

Growth and activity of microbes and microbial processes are greatly affected by environmental factors such as temperature, moisture and substrate availability and all of which are likely to be affected by climate change. Effect of climate change on growth and activities of soil microbes may be direct and indirect. The direct effects include the influence of temperature, changing precipitation and extreme climatic events, whereas indirect effects are due to climate-driven changes which alter soil physicochemical conditions and plant productivity. Since soil matter decomposition is one of most widely contributions of soil microbes to climate change, global warming will accelerate rates of heterotrophic microbial activity, increasing the efflux of CO_2 to the atmosphere. The climate changes will have distinct indirect effects on soil microbial communities and their activity through its influence on vegetation composition and plant growth. Indirect effect of rising atmospheric concentrations of CO_2 on soil microbes is the first mechanism, and the second mechanism is the increased plant photosynthesis and transfer of photosynthate carbon to fine roots and mycorrhizal fungi (Zak et al. 1993; Bardgett Richard et al. 2008) and heterotrophic microbes (Hogberg and Read 2006). It is well-known that elevated/high CO_2 increases plant growth and photosynthesis under nutrient-rich conditions (Curtis and Wang 1998) which in turn increases the flux of carbon to roots and their symbionts and also heterotrophic microbes through root exudation of easily degradable sugars (Fig. 7.1). (Dıaz et al. 1993; Zak et al. 1993).

7.6 Role of Microbes in Combating Climate Change

7.6.1 Climate Change Adaptation

Microorganism can be used to facilitate adaptation to climate change by promoting growth and development and imparting resistance against several abiotic stresses. They offer an opportunity to rely on the biological processes rather than climate change-inducing synthetic chemicals. Soil microorganisms are involved in soil formation, regulate its characteristics, sustain its fertility, break down toxic compounds, enhance sustainable production and ultimately promote ecosystem resilience and sustainability. Microorganisms can be used to manage soil health and ecosystem resilience and to do away with the need for producing and transporting chemical fertilizers.

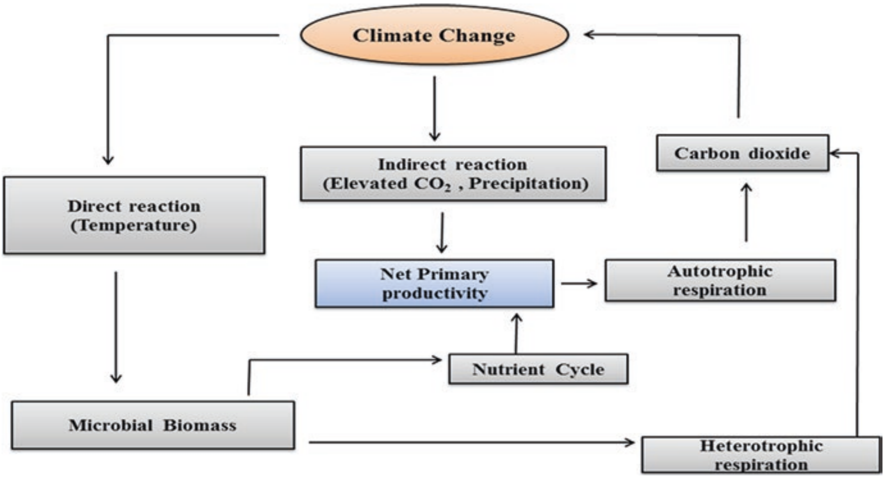

Fig. 7.1 Flow chart presentation of climate change on soil microbial communities and its direction of reaction to global warming through carbon dioxide production

Novel biological control agents can be used to limit the harmful impact of new and emerging pathogens and pests in a changing climate scenario. The most common biological control agents are *Neozygites fresenii* (parasitoid), used to control the cotton pest *Aphis gossypii*, and rust fungus *Maravalia cryptostegiae*, which is used in Australia to control the weed rubber vine. The bacterium *Bacillus thuringiensis*, which produces crystalline toxins that kill Lepidoptera and Diptera larvae, has been used on a large commercial. Both augmentative biological control, i.e. release of large number of previously mass-reared natural enemy in the environment, and conservation biological control, i.e. manipulation of environment to increase the fitness of natural enemies, can help adapt to climate change.

Beneficial plant–microbe interactions are known to stimulate plant growth and enhance their resistance to degenerative diseases and abiotic stresses. Beneficial bacteria when associated with plants improve nutrient acquisition, produce plant growth regulators and alter physiological and biochemical properties of the host plant and therefore help in protecting the plant roots against soilborne pathogens. Bacterial genera such as *Pseudomonas*, *Bacillus*, *Rhizobium*, *Azospirillum*, *Streptomyces* and *Serratia* come under this group. These plant-associated beneficial bacteria can be exploited for faster plant growth and enhanced disease resistance in changing climate conditions. Study shows C4 plant can cope with elevated CO_2 levels when combined with right strains of mycorrhizal fungi (Tang et al. 2009). Recently identified *Rhizobia* species associated with *Medicago sativa* has the potential to operate under various abiotic conditions such as low or high temperature or pH or low levels of organic matter in the soil. Thus the enormous unexplored reservoir of genetic and metabolic microbial diversity provides tremendous opportunity to identify novel genes for pest control, nitrogen fixation and biodegradation with help of recently developed tools such as metagenomics.

7.6.2 Climate Change Mitigation

Soil microbes and their metabolic activity can influence land–atmosphere carbon exchanges in numerous ways, while these can be broadly divided into different groups such as those that affect the ecosystem by methane and carbon dioxide uptake and that also control carbon loss from the soil through methane production and respiration (Fig. 7.1).

Methanotrophs or methane-oxidizing bacteria (MOB), present in aerobic soils, are potential biological sink to mitigate methane emission to the atmosphere. They utilize CH_4 as their sole source of carbon and energy. The methanotrophs can contribute up to 15% to the total global CH_4. However, they are sensitive to environmental perturbations, and they are difficult to isolate due to their slow growth rate and fixed attachment to soil particles. A recently discovered bacterium *Methylokorus infernorum*, found in geothermal areas in acidic and hot environment, utilizes methane gas. These bacteria can consume a huge quantity of methane, i.e. near about 11 kg/year, and also can be helpful in reducing methane emission from methane-producing factories and landfills. In addition to this, *Methylobacillus* bacteria are found to recycle carbon compounds such as methane, methanol and methylated amines. Apart from that there are some naturally occurring microbes that convert carbon dioxide into calcium carbonate. Some group of denitrifying bacteria are known to convert nitrous oxide into nitrogen gas. These microbes have great potential to mitigate GHG emissions.

In addition to this, use of beneficial microorganisms increased productivity, thus affecting GHG budget in terms of GHG emission per unit food production. Benefit accrued by use of beneficial microbes in terms of production can be considered as a contribution of microbe to climate change mitigation.

7.7 Future Prospects and Challenges

Microbial world is the largest uncultivated pool of biodiversity on earth, and till the last century, only a very small fraction, i.e. <10%, is known with respect to its nature and identification (Bhattacharyya and Jha 2012). Although microorganisms constitute the smallest forms of life, they play a vital role in every spectrum of activities within a living organism on earth. Therefore, study based on microbial ecology becomes a significant frontier in the present day of biological science. Soil bacteria sense the chemical-based messages and secrete chemicals of their own that can activate complex plant defences in the plant (Glick 2012). They contribute significantly to the utilization of greenhouse gases (Bardgett Richard et al. 2008), including CO_2, CH_4, N_2O and nitric oxide (NO). Microorganisms play a key role in the crop protection by enhancing disease resistance capacity of plants against the pathogens and exhibiting aggressive activities or substitute as biotic elicitors against different biotic and environmental factors. Among some microbes, fungi can colonize the upper parts of plants and provide protection against various biotic and abiotic like drought, heat, insects pest attack and pathogens (Singh et al. 2011). However, use of microbial-based fertilizer in agricultural practice is still not very popular. The main reasons are uncertainty of results and problems associated with identifying and tracking inoculated strains in the field. Now in the twenty-first century, microbial biotechnology and its application in sustainable development of agriculture are getting better consideration. Conservation of microbial diversity is crucial in the maintenance of species diversity of higher organisms and strategies for plant disease and nutrient management (Colwell and Munneke 1997). Climate change induces adaptation processes in the plants and microorganisms (Grover et al. 2011) and thus changes the ability of plant–microbe relations. An understanding of microbe–climate change feedback and potential positive and negative role of microbes in global climate change is essential to exploit them for climate change adaptation and mitigation.

7.8 Conclusion

Climate change phenomenon such as increase of mean temperature, changing patterns of rain and increasing frequency of extreme climatic events like cyclone, drought and flood will have profound impacts on agriculture. It is utmost necessary to reorient and transform agriculture to make it more resilient to climate change. Microorganisms carry out many vital ecosystem functions that are crucial for plant growth and development such as soil organic matter decomposition, nutrient cycling, N_2 fixation, PGPR activities and acquisition of nutrients through root–mycorrhiza association. Appropriate management and exploitation of beneficial microbial functions such as use of biofertilizer, biological control of disease and pest and plant growth-promoting rhizobacteria can contribute to both climate change adaptation and mitigation. Microorganism can be used to facilitate adaptation to climate change by promoting growth and development and imparting resistance against several abiotic stresses. Soil microbes and their metabolic activity influence land–atmosphere carbon exchanges in various ways. Group of bacteria that use CH_4 as their source of energy and food such as methanothrops can be exploited for climate change mitigation; however isolation, culture and inoculation of these bacteria are still a challenge to be addressed. Climate change affects not only growth and productivity of crop plants but also growth and activity of microbes in rhizosphere directly and indirectly. A proper understanding of microbial ecology and soil–plant–microbe interaction in a changing climate scenario is essential to use microbial technology for climate change adaptation and mitigation.

References

Bardgett Richard D, Freeman C, Ostle Nicholas J (2008) Microbial contributions to climate change through carbon cycle feedbacks. ISME J 2:805–814. https://doi.org/10.1038/ismej.2008.58

Bhattacharyya PN, Jha DK (2012) Plant growth-promoting rhizobacteria (PGPR): emergence in agriculture. World J Microbiol Biotechnol 28:1327–1350

Colwell PF, Munneke HJ (1997) The structure of urban land prices. J Urban Econ 41(3):321–336

Curtis PS, Wang X (1998) A meta-analysis of elevated CO2 effects on woody plant mass, form and physiology. Oecologia 113(3):299–313

deSouza JT (2002) Distribution, diversity and activity of antibiotic-producing pseudomonas spp. Wageningen University dissertation 3260

Dıaz S, Grime JP, Harris J, McPherson E (1993) Evidence of a feedback mechanism limiting plant-response to elevated carbon-dioxide. Nature 364:616–617

FAO (2009) The state of food and agriculture: livestock in the balance. FAO, Rome

García-Fraile P, Menéndez E, Rivas R (2015) Role of bacterial biofertilizers in agriculture and forestry. Bioengineering 2(3):183–205. https://doi.org/10.3934/bioeng.2015.3.183

Glick BR (2012) Plant growth-promoting bacteria: mechanisms and applications. Scientifica 2012:15

Gray EJ, Smith DL (2005) Intracellular and extracellular PGPR: commonalities and distinctions in the plant-bacterium signaling processes. Soil Biol Biochem 37:395–412

Grover M, Ali SZ, Sandhya V, Rasul A, Venkateswarlu B (2011) Role of microorganisms in adaptation of agriculture crops to abiotic stresses. World J Microbiol Biotechnol 27(5):1231–1240

Gyaneshwar P et al (2002) Role of soil microorganisms in improving P nutrition of plants. Plant Soil 245:83–83

Högberg P, Read DJ (2006) Towards a more plant physiological perspective on soil ecology. Trends Ecol Evol 21(10):548–554

Howieson JG, Yates RJ, O'Hara GW, Ryder M, Real D (2005) The interactions of Rhizobium leguminosarum biovar trifolii in nodulation of annual and perennial Trifolium spp. from diverse centres of origin. Aust J Exp Agr 45:199–207

Intergovernmental Panel on Climate Change (IPCC) (2007) Climate change 2007: mitigation of climate change. Contribution of Working Group III to the fourth assessment report of the IPCC

Juma NG (1998) The pedosphere and its dynamics: a systems approach to soil science, vol 1. Quality Color Press Inc., Edmonton. 315 pp

Khan A, Jilani G, Akhtar MS, Naqvi SM, Rasheed M (2009) Phosphorus solubilizing bacteria: occurrence, mechanisms and their role in crop production. J Agric Biol Sci 1:48–58

Lobell DB, Bänziger M, Magorokosho C, Vivek B (2011) Nonlinear heat effects on African maize as evidenced by historical yield trials. Nat Clim Chang 1(1):42–45

Picard C et al (2008) Genotypic and phenotypic diversity in populations of plant-probiotic Pseudomonas spp. colonizing roots. Naturwissenschaften 95:1–16

Selosse Marc-Andre et al (2006) Mycorrhizal networks: des liaisons dangereuses? Trends Ecol Evol 21:621–628

Sharma SB, Sayyed RZ, Trivedi MH, Gobi TA (2013) Phosphate solubilizing microbes: sustainable approach for managing phosphorus deficiency in agricultural soils. SpringerPlus 2:587

Singh LP, Gill SS, Tuteja N (2011) Unraveling the role of fungal symbionts in plant abiotic stress tolerance. Plant Signal Behav 6:175–191

Smith SE et al (2008) Mycorrhizal symbiosis. Academic, London

Tang J, Xu L, Chen X, Hu S (2009) Interaction between C4 barnyard grass and C3 upland rice under elevated CO2: impact of mycorrhizae. Acta Oecol 35:227–235

Walpola BC, Min-Ho Y (2012) Prospectus of phosphate solubilising microorganisms and phosphorus availability in agricultural soils: a review. Afr J Microbiol Res 6:6600–6605

Weller D et al (2002) Microbial populations responsible for specific soil suppressiveness to plant pathogens. Annu Rev Phytopathol 40:309–348

Zak DR, Pregitzer KS, Curtis PS, Teeri JA, Fogel R, Randlett DL (1993) Elevated atmospheric CO_2 and feedback between carbon and nitrogen cycles. Plant Soil 151(1):105–117