Chapter 5
Impact of Climate Change on Soil Microbes Involved in Biogeochemical Cycling

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Abstract Anthropogenic activities have led to the emission of greenhouse gases which have accumulated in the earth's atmosphere over a period of time. The increased concentration of greenhouse gases has increased earth's temperature and has changed weather patterns. The enhanced CO_2 level, warming effect and changing soil moisture conditions have influenced soil microorganism. The microbial communities present in soil and the interactions taking place in terrestrial environment are extremely diverse and complex. The effect of climate change on soil microbial communities includes changes in microbial community composition, species abundance, diversity, survival and resilience, changes in enzyme production, and changes in interactions of microbes with roots of plants, production and sequestration of atmospheric gases (e.g. CO_2, CH_4, N_2O), utilization of soil nutrients and organic matter, etc. Further, the bidirectional nature of interactions where physical environment influences microorganisms and microorganisms in turn can impact environmental conditions, making it difficult to understand the effect of climate change. These microorganisms are involved in various biological processes associated with biogeochemical cycle. Thus, any change in microbial communities also affects the nutrient cycling through biogeochemical cycles. This chapter focuses on the effect of climate change on soil microorganisms and the impact on various microbial processes associated with carbon and nitrogen cycle.

Keywords Biological processes · Carbon cycle · Climate change · Extreme weather events · Nitrogen cycle · Soil microorganisms

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5.1 Introduction

Due to the increased emission of greenhouse gases, there is a change in the climate, and it is predicted that the earth can become warmer by 5 °C by the end of this century. This changing climate has a profound impact on natural environment and human wellbeing. Climate change can strongly influence both abiotic and biotic interactions taking place in the environment. Biogeochemical cycling of nutrients is no exception (Frank et al. 2015). Climate change also affects terrestrial ecosystem. The microorganisms play an important role in maintaining the structure and functioning of terrestrial ecosystem. Climate change can affect soil microorganisms in many ways, including changes in species composition, abundance and distribution. It can also have direct and/or indirect effect on microorganisms causing changes in microbial community composition and/or enhanced or reduced physiological functions. Microbial communities in nature are complex and the interaction among different microorganisms is also varied. Thus, the response of soil microbes to changing environmental conditions is influenced by all these factors. Studies have shown that there is a change in biodiversity and function of ecosystem due to the impact of climate change. Soil microorganism interacts not only among themselves but also with flora and fauna of the region; thus, the interactions are extremely complex, making prediction of climate change-induced alteration very difficult. At the same time, the importance of soil microbes, especially those involved in biogeochemical cycles, stresses the need to do detailed analysis of the impact of climate change (Classen et al. 2015).

The interaction in between climate change and soil microbes is bidirectional. The soil acts as a sink for CO_2, while microbial processes taking place in soil lead to the emission of greenhouse gases like CO_2, CH_4, N_2O, etc. The microbial communities present in soil participate actively in various processes of biogeochemical cycles and regulate the movements of essential nutrients like carbon and nitrogen (French et al. 2009). Emission of CO_2 by various soil microbial processes can contribute up to 10% of total atmospheric CO_2; thus, soil microbial processes can influence the atmospheric factors at a global level (French et al. 2009; Mandal and Neenu 2012; Gougoulias et al. 2014). Microorganisms differ in their physiology, sensitivity, resilience and abundance; thus, changing physical conditions in terrestrial ecosystem has both direct and indirect impacts on them. When microorganism involved in key ecological processes like denitrification, nitrification, lignin degradation, etc. are affected, the functioning of ecosystem is also affected (Classen et al. 2015).

Various biological processes occurring in the terrestrial ecosystem have significant impact on the earth systems at a global scale. Carbon and nitrogen are the two most important nutrients required to sustain life. Their cycling among the various compartments of earth, atmosphere, lithosphere and hydrosphere is very important to sustain life and its processes. These biogeochemical cycles involve a number of biological processes mainly driven by soil microorganisms. The various processes for carbon cycle are photosynthesis, respiration, methanogenesis, fermentation, decomposition, etc. Nitrogen cycle involves biological processes like nitrification, denitrification, ammonification, etc. The climatic conditions have strong influence on the response and survival of soil microorganisms. These microbes, in turn, can have significant impact on environment by controlling the source and sink activities associated with carbon and nitrogen. Studies have shown that terrestrial ecosystem serves as a sink for CO_2. However, carbon sequestration also depends on the nitrogen content of the soil. Soils poor in nitrogen show reduced carbon fixation, and addition of nitrogen fertilizers promotes carbon sequestration as formation of soil organic matter requires a suitable C/N ratio along with other nutrients (French et al. 2009).

This chapter reviews the effect of climate change on microbial communities associated with carbon and nitrogen biogeochemical cycles. The chapter deals with the issue of the impact of changing abiotic conditions like increase in temperature, change in precipitation or increased CO_2 on structure and functioning of microbial communities. Studies related to the effect of climate change on microbial diversity, abundance, resilience and functioning are discussed. The changes in plant–microbe interaction, soil enzymes, rhizosphere, plant–microbe symbiotic relationships, pathogens and the associated changes in carbon and nitrogen cycles are also discussed.

5.2 Carbon Cycle and Microorganisms

Carbon is the essential nutrient for all life forms. In nature, it exists in both inorganic and organic forms. Microbes and plants interconvert the two forms of carbon and bring about its circulation among different compartments of environment, i.e. hydrosphere, atmosphere and lithosphere. The global carbon cycle is mainly driven by microbial communities, involved in the processes of fixing atmospheric C, plant growth and transformation and degradation of soil organic matter. Carbon is present in the atmosphere as CO_2 and CH_4. It is also present in the earth's crust in many inorganic forms like limestone and kerogens and in organic forms in soil. The process of converting C present in the atmosphere into organic form is called carbon fixation. In aerobic environment, photosynthesis is the dominant process for fixing atmospheric carbon. In this process, atmospheric CO_2 is converted into organic compounds and sunlight is used as a source of energy. Photosynthesis is performed mainly by plants and photosynthetic algae. Apart from photosynthesis, chemoautotrophic microorganisms (cyanobacteria, bacteria and some protozoa) also convert inorganic C compounds into organic compounds. The organic matter thus produced is consumed by animals and microbes for growth and maintaining their metabolic processes. As a result of these metabolic activities, CO_2 is generated and released in the environment. This process is called respiration. Terrestrial carbon cycle is a balance in between CO_2 fixed during photosynthesis and CO_2 released during respiration and organic matter decomposition. When living organisms die, their cells are transformed and decomposed by heterotrophs and carbon is released (mineralization). In anaerobic environment, microorganisms use organic compounds for obtaining energy and the process is called fermentation. Some of the commonly occurring fermenters are green and purple sulphur bacteria, *Thiobacillus ferrooxidans*, *Bacteroides succinogenes*, *Clostridium butyricum*, *Syntrophomonas* sp., etc. Fermentation is responsible for the release of CO_2 and CH_4 in environment. CO_2 is the major source of carbon followed by methane (CH_4). Methane exists in anaerobic environments. Methanogens are anaerobic archaebacteria that convert organic matter into methane by methanogenesis. Another group of bacteria, methanotrophs or methane-oxidizing bacteria, is a special group of aerobic bacteria capable of utilizing methane as an only source to satisfy carbon and energy requirements. Methanotrophs live at the boundary of aerobic and anaerobic environment so that they can have easy access to methane from anaerobic side and oxygen is available to them from aerobic side. The major microbial processes involved in carbon cycle are CO_2 fixation, methane production and utilization, respiration and decomposition of organic matter (Abatenh et al. 2018). Figure 5.1 shows the details of carbon cycle.

5.3 Effect of Climate Change on Soil Microorganisms of Carbon Cycle

Climate has a strong influence on the abiotic factors in the ecosystem. The growth, survival and activity of microbes are strongly regulated by abiotic conditions. Thus, climate change-induced variation in abiotic conditions can regulate and alter dynamics of microbial populations present. The two most important abiotic factors are temperature and moisture. The changes they can induce include abundance, composition and function of microorganisms. The growth and activity of any microorganism are its individual characteristics and can vary independently. Say, a change in abiotic condition induced higher activity; however, the growth of microorganism might reduce or might show lower biomass. Thus, growth and activity are two independent aspects of microbes and can respond differently to same changes in abiotic conditions (Mandal and Neenu 2012).

5.3.1 Effect of Enhanced CO_2 on Carbon Cycle Microbes

The amount of carbon locked in soil in organic form is almost three times the carbon available in the atmosphere. Annually, about 8% of carbon is circulated by carbon biogeochemical cycle in between the atmosphere and lithosphere. If the process of respiration and decomposition stops, then 100% of carbon present in the atmosphere will be fixed to organic matter in soil in about 12 years (Gougoulias et al. 2014). At present, the amount of carbon fixed by photosynthesis and autotrophic

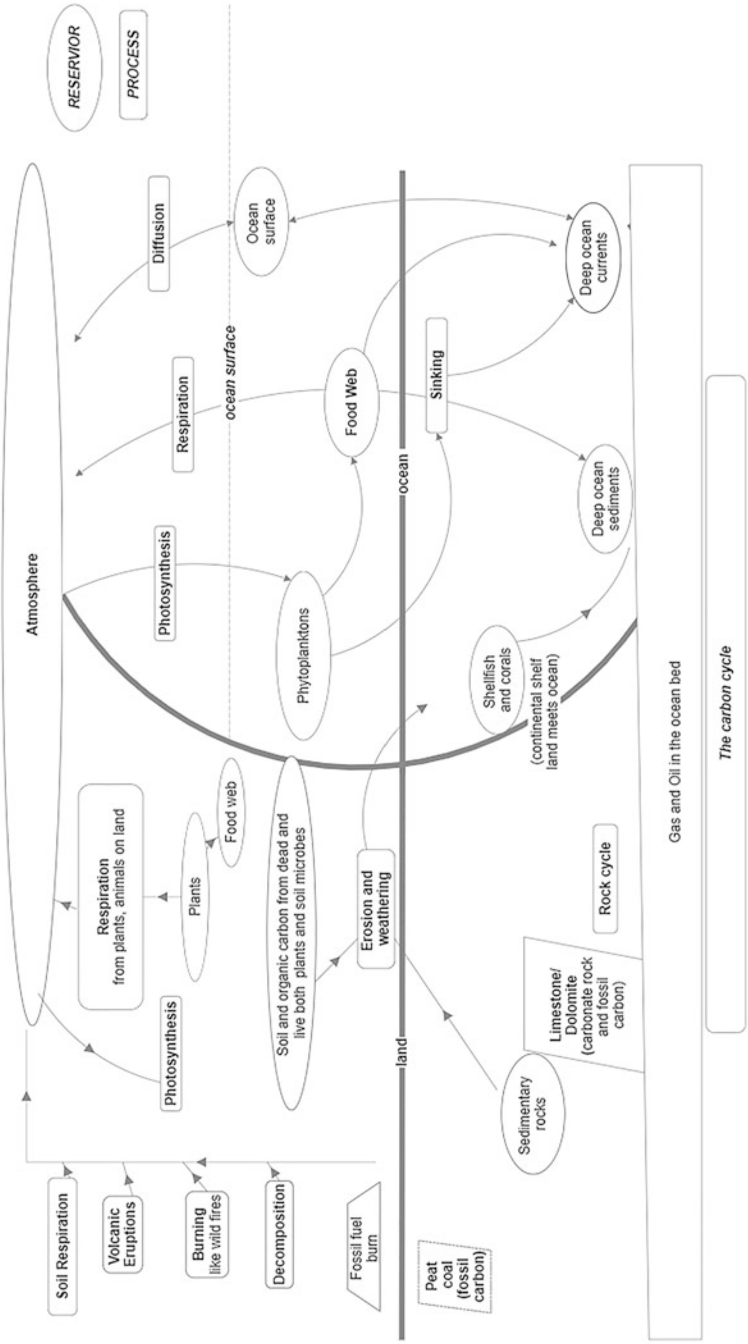

Fig. 5.1 The biogeochemical cycle of carbon

microorganism is almost 25% more than the carbon liberated during respiration. Thus, terrestrial carbon sequestration acts as a sink for CO_2.

Anthropogenic activities have disturbed the natural balance of the biogeochemical cycles. Burning of fossil fuels and cultivation of land have increased the emission of CO_2, CO, etc. Increase in atmospheric CO_2 content acts as fertilizer for photosynthesis, thereby stimulating growth. More root exudates are produced by plants and these organic substrates in turn enhance microbial activities in rhizosphere. Studies have reported changes in microbial community composition and activity. A study reported 121% increase in biomass of microorganism after treatment with CO_2 (690 ppm) in open top chambers for 22 weeks (French et al. 2009). Some studies have reported increased dominance of *Pseudomonas* spp. at elevated CO_2, some studies using molecular techniques have confirmed changes in community structure for bacteria as well as fungi, but some studies have reported no change (French et al. 2009). Arbuscular mycorrhizal fungi (AMF) form symbiotic relationship in between plants and fungi. Fungi colonize the roots of host plants and create vast connections between roots of plant and surrounding soil. This increases the surface area for nutrient uptake. An enhanced level of CO_2 promotes photosynthesis. More carbohydrates are available for roots. This promotes the growth of AMF. Thus, enhanced ambient CO_2 levels indirectly increase AMF development and promote symbiotic relationship (Choi et al. 2005; French et al. 2009).

The microbial decomposition and respiration also increased (French et al. 2009; Gougoulias et al. 2014). This in turn increases carbon mineralization, and more CO_2 is released in the environment. These changes will disturb the balance between carbon fixation and carbon mineralization. The processes are very diverse and complex. Thus, the net effect of the increase in CO_2 content in the atmosphere might favour carbon sink (photosynthesis) as well as carbon sources (decomposition and respiration). It is difficult to predict the outcome in the future. However, few models have predicted that increase in atmospheric CO_2 will lead to increased carbon emission (Gougoulias et al. 2014). Studies have suggested that increase in CO_2 will lead to enhanced photosynthesis by plants. The amount of litter generated by plants will also increase. This litter may alter the soil chemical and physical properties. Such changes can alter not only composition but also function of the microbial communities present there. Elevated CO_2 also promotes root growth, thus including changes in rhizosphere (Mandal and Neenu 2012). The published studies have also reported that the increasing CO_2 had no significant effect on microbial growth and activity (Kandeler et al. 2006; Pinay et al. 2007). Drissner et al. (2007) conducted a study to see the effect of elevated CO_2 on the soil enzymes commonly involved with biogeochemical cycles. In spring season, the activity of enzymes increases, urease (23.8%), xylanase (22.9%), protease (40.2%), invertase (36.2%) and alkaline phosphomonoesterase (54.1%) activities. However, in autumn season, enzyme activity decreased by 3–12%.

The effect on climate change on microbes can be evaluated at individual, community or global level. A study by Collins et al. (2008) evaluated the effect of CO_2 enrichment on phytoplankton community. Different microbial species respond differently to changes in environment. Also, by analysing evolutionary or physiological traits, it is difficult to predict the microbial response. Same microbial species may respond differently for single strain community and multi-strain community. For single strain communities, long-term CO_2 enrichment experiments enhanced biomass production. However, in multi-strain communities, the long-term CO_2 enrichment experiments lead to decline in CO_2 fixation. The difference in responses might be due to competitive interactions present in multispecies communities (Collins et al. 2008).

5.3.2 Effect of Drought and Increased Moisture on Carbon Cycle Microbes

The impact of climate change on biogeochemical cycle not only depends on the diversity and abundance of microorganisms but also on the prevalent environmental conditions in the ecosystem (Bardgett et al. 2008). In forest ecosystem, increase in severity and frequency of droughts will make the soil water deficient and dry. Various studies have shown that the moisture content may decrease to the level that it negatively affects microbial activity. The rate of decomposition and respiration reduces. The activity of phenol oxidase and amount of fungal and bacterial biomass also reduce (Nardo et al. 2004; Krivtsov et al. 2006). However, if similar changes occur in wetland or peatland, the effect will be opposite. Increased dry conditions will lower the water table in the region, thereby converting anaerobic soil into aerobic. This change will favour degradation and microbial respiration. Studies have shown that the activity of phenol oxidases increases (Freeman et al. 2004; Zibilske and Bradford 2007). Wetlands and peatlands have huge stock of organic matter. If the dry condition prevails, the level of oxygen in soil increases and CO_2 efflux increases. At the same time, the activity of methanogens is inhibited. These changes might have significant impact on global carbon cycle (Bardgett et al. 2008).

Global warming is leading to abrupt climate changes like increase in severity and frequency of drought, increased rainfall and increased episodes of extreme climate. Such changes in climate affect the global pattern for production and decomposition of organic matter. Drought can change the carbon allocation in between roots and foliage and thus can affect below-ground cycling of carbon and other nutrients. Rhizosphere is a zone where interactions in between roots and root-associated microorganisms take place. Drought can disrupt the various processes taking place in rhizosphere. Sanaullah et al. (2011) studied the changes in the microbial biomass and enzyme activity (xylanase, β-cellobiosidase, β-glucosidase, chitinase) in rhizosphere of grasses, grown as monoculture and mixed culture. It was observed that lesser carbon was allocated to shoot as compared to root. No trend was observed for changes in microbial biomass in monoculture conditions. However, in mixed culture, there was an increase in microbial biomass. Unplanted soil showed most adverse drought response with severe decline in enzyme activity of all the enzymes studied. The enzyme activity was lower in mixed plantations as compared with monoculture. The enzymes studied (xylanase, β-cellobiosidase, β-glucosidase, chitinase) are involved in decomposition of organic matter, and we can say that due to drought, the decomposition process will be slower in mixed plantations as compared with monoculture.

The response of microbes for change in moisture content also varies from region to region. The microbes inhabiting dry and arid place will have lower capability to respond to higher moisture content (Meisner et al. 2013). Due to climate change, there will be not only increasing episodes of drought and flood but also pulsed rain events where wet and dry spell will alternate. Studies have shown that microbial community and their functioning change with wet and dry spell with transition phases. The microbial activity is high during wet spell and lower during dry spell. However, some studies have indicated that dry spell exposes old C pools, and during wet spell, the microbial activity becomes so high that it is able to compensate the reduction in activity during dry spell (Collins et al. 2008; Evans et al. 2012; Meisner et al. 2013).

The duration of the study also has profound influence on the results. A study was conducted in Mediterranean-type grassland ecosystem. The effect of natural process of rainfall and dry period was studied. Short-term effects were studied for changes in the structure and function of microbial community. It was observed that microbial communities, especially bacteria, respond quickly for the rewetting for soil after a dry period. Rainfall was quickly followed by pulses of release of nutrients like carbon and nitrogen. Most of the abundant microbial communities (*Actinobacteria*, *Acidobacteria*, *Proteobacteria*, *Bacteroidetes*, *Firmicutes*, *Cyanobacteria*, *Verrucomicrobia*) showed strong correlation for moisture and available carbon. Many studies have reported that microbial communities are resilient to changes in moisture; however, most of them involve longer durations. Results can vary significantly with duration of the study (Cruz-Martínez et al. 2012).

5.3.3 Effect of Rise in Temperature on Carbon Cycle Microbes

One of the effects of climate change predicted is the overall temperature of earth will increase by 1–5 °C (IPCC 2007). It is generally believed that global warming will increase the degradation of organic matter, and thus the C flux from terrestrial ecosystems to atmosphere will increase. Increase in temperature can affect microbial community composition as well as physiological functioning. Studies have shown that bacteria play more important role in determining the rate of respiration as compared with fungi (Keiblinger et al. 2010). Most of the warming studies have shown that there is not much effect on microbial biomass due to rise in temperature. However, the changes in microbial community composition are varied. They can be change in fungal abundance, change in abundance of gram-positive bacteria, decrease in gram-negative bacteria or no change in microbial community structure

(Schindlbacher et al. 2011). A 5-year warming study was conducted in forest of Achenkirch, Austria. No change was observed in terms of microbial biomass or community structure over the entire period of the study (Schindlbacher et al. 2011). Zhang et al. (2005) studied warming effect on tall grass prairie for 2 years. The increase in fungal abundance was observed. Similar results were also reported by Castro et al. (2010). However, the increase in fungal abundance was an indirect effect caused due to changes in plant community. Warming may also lead to gradual decline in available decomposable matter. This change may also alter community composition. Thus, there are many direct and indirect factors affecting microbial processes (Schindlbacher et al. 2011). The soil respiration rate and thus CO_2 release increased as a result of warming of soil. This change can be linked to higher turnover rate and changes in substrate utilization by microorganisms. It was also observed that microbes were under stress and their respiration rate increased (Schindlbacher et al. 2011). Another study was conducted for 7 years (2002–2009) at deciduous forest in New England to evaluate the heating effect on CO_2 emission and sequestration. In warmed plots, temperature was maintained 5 °C more than the ambient temperature. Ambient temperature varied from 20 °C in summer to −6 °C in winter. Rainfall was evenly distributed. Increase in temperature promoted microbial activity, higher degradation of organic matter was observed and thus CO_2 emission increased. Warming also increased the storage of carbon in plants as compared with control plots. By the end of 7 years, the increased amount of carbon stored in plants was able to offset the increased CO_2 emission effect (Melillo et al. 2011).

Rise in atmospheric temperature or global warming has greatly affected the microbial functioning as the microbial processes are temperature sensitive. Many studies have explored the impact of rising temperature on soil microbes. However, there is no clear trend. Results also vary with experimental conditions like duration of study (short term or long term), or lab study or field study, single factor or multiple factors, etc. (Classen et al. 2015). Most of the studies have reported that the decomposition of organic matter and microbial respiration increase with rising temperature (Bradford et al. 2008; Sistla and Schimel 2013). Possible reasons for these changes can be changes in the structure of microbial community, substrate availability, quality and quantity of litter and relative abundance of labile carbon versus soil organic carbon (French et al. 2009). However, these changes can be for short duration. With time, as the labile C pool decreases in soil, the microbial activity also reduces. There might be change in microbial composition and functioning. Microbes respond to these changes by adaptation, evolution and interactions. The changes are diverse and complex (Bradford et al. 2008; French et al. 2009; Mandal and Neenu 2012; Sistla and Schimel 2013; Gougoulias et al. 2014).

An important indirect effect of rising temperature is greater loss of moisture from soil, creating drought-like conditions. Lack of moisture may negatively impact the availability of nutrients. The fast-growing bacterial community is more prone to adverse effect as compared with slow-growing fungal community. The changes in fungal community composition are usually more evident as compared with bacteria, showing better adaptability of fungi (Blankinship et al. 2011).

5.3.4 Combined Effect of Different Climate Change Factors on Carbon Cycle Microbes

Most of the studies have evaluated the effect of single factor while studying climate change and biological systems. However, in real scenario, there will be more than one factor affecting the environment. The net effect might be additive, antagonistic or no change. In nature, the changes in climatic conditions will not be individualistic. That is, changes in temperature will be overlapped with changes in CO_2 concentration, precipitation and so on. Thus, it is important to study the effect of microorganisms with variation in more than one abiotic condition. Effects of variation in temperature (ambient, 3 °C), precipitation (wet and dry) and CO_2 concentration (ambient, 300 ppm) were studied on bacterial and fungal diversity in oil field ecosystem (Mandal and Neenu 2012). Bacterial diversity increased in case of high temperature and high CO_2 concentration. The plots with high temperature and ambient CO_2 concentration showed decreased bacterial diversity. Fungal diversity increased in plots with high temperature (Mandal and Neenu 2012).

Studies combining the effect of stress due to climate change have often reported that microbial communities experiencing stress often trade growth for stress tolerance traits. Combined effect of warming (5 °C above ambient) and four freeze–thaw cycles on soil microorganisms was studies at Hubbard Brook Experimental Forest in the northeastern United States. The brown rot fungi and plant pathogens were favoured by rise in temperature, while growth of arbuscular mycorrhizal fungi (AMF) especially *Glomus* reduced. Warming and freeze–thaw cycle together promoted animal pathogens (genera *Trichosporon* and *Metarhizium*) and AMF recovered. The copiotrophic and cellulose degrading bacteria were also suppressed (Garcia et al. 2020). A study by Sheik et al. (2011) evaluated the combined effect of high temperature and drought on microbial communities of Oklahoma prairie soil, USA. It was observed that during the periods of normal rainfall and increase in temperature (2 °C above ambient), the microbial biomass increased by 40–150% but diversity decreased; thus, the composition changed. During the period of drought, the slight increase of 2 °C lead to severe drying of the soil and microbial population decreased by 50–80%. However, there was no long-term effect on community composition as species diversity, richness and evenness improved. May be under stressed conditions, fewer phylotypes were active (Sheik et al. 2011). All the physiological functions of the microorganisms are mediated through enzymes. Studies have shown that during stress, there might be a change in resource allocation, preference being given to enzyme production. This will help in optimizing the use of limited resources available (Steinweg et al. 2013). Microbial enzymes and microbial biomass were measured in a study conducted in an old abandoned field at Boston-Area Climate Experiment (BACE), USA. Combined effect of higher temperature (4 °C above ambient), lower rainfall (50% of normal) and higher rainfall (150% of normal) was evaluated. It was observed that microbial enzyme production increased with increasing temperature, while microbial biomass decreased. Possible reason can be allocation of resources for enzyme production changed. Thus, the popular view that changes in microbial biomass are followed by changes in microbial enzyme production was challenged (Steinweg et al. 2013).

5.3.5 *Effect of Extreme Climatic Events on Carbon Cycle Microbes*

Studies have shown that the frequency and severity of extreme weather events have increased due to climate change. This is in addition to the gradual effect climate change has on environmental conditions. The extreme weather events include heat waves, frosts, extreme drought, heavy precipitation, wind storms, etc. The past few years have witnessed many incidences of extreme weathers worldwide and also in India. Tables 5.1 and 5.2 summarize few events related to climate change and extreme events that occur worldwide and in India, respectively. Extreme weather events are considered as disturbances or pulse events that last for a short duration but have a strong impact on the surroundings. The effect can be categorized into four types: direct and concurrent like reduced productivity due to drought, indirect and concurrent like change in organic matter composition of soil due to forest fire caused by lightening, direct and lagged effect like reduced flowering and fruiting due to loss of fertile soil during flash floods and indirect and lagged effect like reduced productivity due to increased pest and pathogen population (Frank et al. 2015).

The ecosystems may experience huge fluctuations in their structure and function due to exposure to extreme climate events. These disturbances can sometimes be strong enough to cause abrupt change from one ecosystem state to another. Sometimes, ecosystems show good resistance and resilience (recovery) and are able to maintain their original state after extreme climate pulse disturbance. If these disturbances reoccur, then changes are inevitable. Different microorganisms adapt to different strategies to deal with disturbances. Members of phylum *Actinobacteria*, commonly found in soils of dry regions, have high tolerance for desiccation or are resistant to drying, while bacteria belonging to phylum *Acidobacteria* survive drought as they are more resilient and recover fast owing to fast growth strategy (Bardgett and Caruso 2020). *Actinobacteria* has oligotrophic characters and shows low growth rate and higher efficiency for resource utilization, but is resistant to change. *Acidobacteria* is copiotrophic, characterized by higher growth rate and lower efficiency for using resources, being resilient (Bardgett and Caruso 2020). Since there are many different types of extreme weather events, their effects also vary accordingly. For example, drought has direct concurrent effect on reduced enzyme activity of microbes. Recurrent droughts might alter the regional microbial community composition favouring drought-resistant species. This in turn will impact CO_2 sequestration and emission. If the extreme event is flash flood, then the top fertile soil is washed off, and the change in ecosystem can be so drastic that it might not be able to recover to its original state (Frank et al. 2015).

Table 5.1 Some of the natural disasters occurring worldwide due to climate change

Event	Year	Location	Details of event	Damage occurred	References
World					
Floods	2020	Indonesia	Coastal cities of Indonesia see frequent floods due to rising water level and excessive rainfall across local watersheds	Capital city Jakarta suffers from floods killing 67 people and displacing 300,000 people	Karyono TH, Vale R, Vale B (2019) Sustainable Building and Built Environments to Mitigate Climate Change in the Tropics: Conceptual and Practical Approaches. Springer
Bushfires	1995–2005, 2020	Australia	Most fire-prone continents suffered extreme fire in 2020. Changing climate and warming can result in dry weather, making the spread of small fires	Many species got burned, massive loss of life (animal and human) occurred, ecosystem was completely destroyed	Russell-Smith J, Yates C & Whitehead P et al. (2007) Bushfires 'down under': Patterns and implications of contemporary Australian landscape burning. Inter J Wildland Fire. 16. https://doi.org/10.1071/WF07018
Cyclone	2019	Southern Africa	Cyclones Idai and Kenneth hit Zimbabwe, Malawi, Mozambique of southeastern Africa simultaneously. Idai caused massive rainfall resulting in mudslides, extensive flooding and collapsing of dam	Destruction from wind and high-intensity rainfall, dam failure all costed lives and livelihood destruction and economic loss too	Cook N (2019) Cyclones Idai and Kenneth in Southeastern Africa: Humanitarian and Recovery Response in Brief. Congressional Research Service
Drought	2010–2011	East Africa	Drought caused by natural variability shifts in ocean temperature and air pressure in 2010 got more enhanced in 2011 with addition of Anthropocene activities. Climate change was held responsible for drought which has destroyed these areas of Africa	Majorly influenced by La Niña which impacted many countries brought drought to Africa. Everything from livestock to dairy and vegetation got destroyed resulting in famines	Lott FC, Christidis N, Stott PA (2013) Can the 2011 East African drought be attributed tohuman-induced climate change?. Geophys Res Lett. 40:1177–1181. doi:https://doi.org/10.1002/grl.50235
Ocean acidification	2016, 2017, 2020	Great Barrier Reef, Australia	As the ocean temperature rises, it results in coral bleaching. The coral in the Great Barrier Reef are very	Loss of various important species and food for other marine lives are all	The Guardian: https://www.theguardian.com/environment/2020/apr/07/great-barrier-reefs-

			sensitive to temperature and turn white under heat stress from water. This is frequently occurring and destroying the whole barrier reef	destroyed in repetitive bleaching of corals	third-mass-bleaching-in-five-years-the-most-widespread-ever
Algal bloom	2003	Antarctica	Within the 5 km of penguin colonies, algal bloom has been recorded and the nitrates of seabird and seal excrement are believed to be their food sources. This results in potential warming as green algae do not reflect sunlight completely, and this could cause temperature rise and melting of glaciers	Melting of Antarctica glaciers could lead to overall rise in water level drowning major coastline cities and destroying natural habitat of Antarctica	Kol E, Flint EA (1968) Algae in green ice from the Balleny Islands, Antarctica, New Zealand Journal of Botany, 6:3, 249–261, DOI: https://doi.org/10.1080/0028825X.1968.10428810
Eutrophication	2016	Australia	It resulted in unprecedented water level decline in lower lakes of Murray–Darling basin. Due to droughts, water acidification has increased along with salinity and eutrophication processes	This impacts the quality of water and aquatic biomes severely. And generally the water cannot be used for any other purposes	Li S, Bush RT, Maoo R et al. (2016) Extreme drought causes distinct water acidification and eutrophication in the Lower Lakes (Lakes Alexandrina and Albert), Australia. J Hydrol, doi: https://doi.org/10.1016/j.jhydrol.2016.11.015
Wildfires	2019	Amazon	In Brazil and Bolivia, large fires took place exceeding community and country capacity	Extensive loss of homes, loss of communities residing in the deep interior, crops, livestock and water supply system	Brando P, Macedo M, Silverio D et al. (2020) Amazon wildfires: Scenes from a foreseeable disaster
Hurricane	2020	Atlantic hurricane	A series of 20 tropical storms and 20 tropical hurricanes and 1 major hurricane occurred in the Atlantic region in the first half of 2020	More than 1 billion dollar of economic loss has occurred. 100 people have lost their lives	National hurricane center and Central Pacific Hurricane center (2020) 2020 Atlantic Hurricane season. Accessed on 17 September

Table 5.2 Some of the natural disasters occurring in India due to climate change

Event	Year	Location	Details of event	Damage occurred	References
India					
Drought	2004–2010	Bundelkhand	Historically droughts occurred every 16 years in the nineteenth century in Bundelkhand region, but with passing times, Anthropocene activities have brought out climatic changes and unorganized development has led to frequent droughts in the region, that is, from 2004 to 2010, this region faced drought frequently and severely. Although surrounded by Yamuna River and its tributaries, because of temperature rise, increased greenhouse gases, urbanization, etc., disasters have occurred	Droughts have caused crop failure and extreme debts, resulting in the death of more than 400 farmers because of suicide and starvation. Many residents had to mass relocate. From extremely rich, lush greenery, abundant water and glorious history, the region has converted into its poorest state with lack of food, water, fodder fuel, etc. with sparse vegetation. Along with climatic disaster, this is also a socioeconomic disaster	Gupta AK, Nair SS, Ghosh O et al. (2014) Bundelkhand Drought: Retrospective Analysis and Way Ahead. National Institute of Disaster Management. New Delhi, P 148
North Indian cold waves	2010–2011	Uttar Pradesh, Haryana, Punjab	A rapid decline in temperature within 24 h called the cold waves was felt severely in north Indian region. A temperature dropped to minus 26 degree in Kashmir and Leh region, while Mount Abu, Rajasthan, became the coldest desert with temperature drop to 4.2 degrees. Due to lack of any western disturbances, the cold waves persisted, resulting in the death of 650 people	Cold waves damage the agriculture and lives killing 650 people. Many viruses and influenza are believe to prevail in cold places more actively, so these waves pose potential threat for epidemic	Bhatla R, Pant M, Singh D et al. (2020) Evaluation of cold wave events over Indo-Gangetic Plain in India. J Agrometeorology 22 (2): 233–238

Cloud bursting, flash floods and landslides	2013	Uttarakhand	Cloud bursting (extreme rainfall >100 mm/h) due to loaded monsoon cloud coming from the Bay of Bengal and Arabian Sea over the Himalayan belt resulted in extreme flash floods on the hills of Uttarakhand causing massive destruction. The Chorabari Glacier melted abnormally fast flooding the Mandakini River causing this destruction. The debris from all the flooded area blocked the routes and cut-off the area from aid reach. The floods also triggered severe landslides adding further to the miseries	More than 5000 people went missing, and the death toll was around 5748. Huge loss to life and property making people homeless and creating potential endemic situation health-wise	Pradeepkumar AP, Behr FJ, Illiyas FT et al. (2014) Proc. 2nd Disaster, Risk and Vulnerability Conference 2014 (DRVC2014) 24–26 April 2014 Dept of Geology, Uni Kerala, Trivandrum, India pp. 57–64 ISBN 9788192344928
Floods	2014	Jammu and Kashmir	Due to severe rain for almost a week and overflowing channels, it caused floods on 6 September 2014 in J&K. The possible cause behind this massive disaster is believed to be climate change caused by Anthropocene activities over centuries	30% of the state was submerged in flood causing thousands of people stranded in their home. 400 villages were fully submerged and 2225 villages were partially submerged and 300 were completely cut-off from other parts of the area. Hundreds of lives were taken and rescue was even more difficult as flood water won't go down at all. Jhelum River was flowing 1 m above its embankment and swelled to a larger scale in hundreds of square km	Tabish SA, Nabil S (2015) Epic Tragedy: Jammu & Kashmir Floods: A Clarion Call. Emerg Med (Los Angel) 5: 233. Doi: https://doi.org/10.4172/2165-7548.1000233
Forest fires	2015–2016	Uttarakhand	Wildfires affected the 13 districts of the state of Uttarakhand. The causes behind these forest fires are believed to be dry weather, low moisture and	This has damaged nearly 4000 hectares of forest cover, destroying biomes and forest ecosystems hugely and killing 9 people and	Dalei N (2016) Forest Fires in Indian State of Uttarakhand. Eurasia Review

(continued)

Table 5.2 (continued)

Event	Year	Location	Details of event	Damage occurred	References
			humidity and deficit vapour pressure that allow fires to spread unconditionally. The heat waves in the summer in the state had promoted the conditions even more. Carelessness of locals as well unsupervised burning of pine needles, litter, etc. in forest with dry climatic conditions have costed the state a lot	injuring many. Glaciers of Himalayas have also been affected by carbon black deposits from smoke, and because ashes have high temperature-absorbing capacity, they may have enhanced the melting of glaciers. Flowing water may have toxic pollutants. 10,000 people had to relocate to avoid the fire	
Avalanche	2016	Siachen Glacier avalanche	In February, an avalanche hit the Siachen Glacier region which is an extremely important region between India and Pakistan border	10 soldiers were killed trapped inside the snow with temperature below −45 degrees. From 1984, 870 soldiers have died due to these major avalanches hitting the region	Wikipedia contributors. Siachen conflict. Wikipedia, the free encyclopedia. Available at: https://en.wikipedia.org/w/index.php?title=Siachen_conflict&oldid=978007208. Accessed September 16, 2020
Storm dust	2018	North India	High-velocity dust storms swept across parts of North India. Dust storm initiated in monsoon season and thunderstorm forecast with high winds were predicted, yet storm came in period of high temperature and increased weather intensity	Many people were killed in UP, Rajasthan, and other states of North India. Huge amount of debris brought along with the storm caused more destruction to lives, infrastructure, etc.	Gupta S (2018) More than 110 killed by high-intensity dust storm in India. CNN. Retrieved 3 May 2018.Accessed 16 September2020
Flash floods	2018	Kerala	Massive destruction caused due to heavy precipitation resulting in flash floods and spilling of dams in Kerala in 2018	Thousands of lives and livestock and animals were washed away or dead. The catastrophe is extreme in the past 100 years	Srivastava, Saikia P, Pandey AC et al. (2020) Evaluating the 2018 extreme flood hazard events in Kerala, India. Remote Sensing Letters 11(5):436–445

Invasion of desert locusts	2020	Rajasthan, Punjab and Gujarat	Invasion of locusts occurred in April 2020 in Rajasthan, Gujarat, Punjab and some part of Delhi. Locust swarm in group and are gluttonous insects consuming 2 g/ each of the crops. They usually bred in high humidity with wind and erratic rainfall. As the country had many rainfalls due to various low pressure disturbances from the west (mid-west Atlantic Ocean), it creates a perfect breeding ground for locusts. These insects travel at 100–200 km/day and consist of 50–100 b locusts per group	Massive destruction to crop fields and huge damage to food production industries. Severe losses to farmers financially. These outbreaks have been proving a great threat to food security and are frequently occurring because of severe climate change especially frequent rainfall, usually as a result of high humidity	Sankar PM, Shreedevasena S (2020) Desert Locusts (Schistocerca gregaria) – A Global Threatening Transboundary Pest for Food Security. Research Today Spl. 2(5): 389–391

5.3.6 Impact of Climate Change on Plant and Soil Microbe Interactions

Climate change has led to increase in temperature and thus, at some places, the plants are migrating to higher latitudes. The changes are drastic that the whole ecosystem has changed. For example, in the Arctic, woody shrubs have been replaced by grasses (Pearson et al. 2013). In soil, many microbial communities are closely associated with plants. This relationship is mutually beneficial and sometimes can have a great influence in terms of adaptation and survival. Changes in plant community in a region can affect microbial communities in many different ways. The microbial community might follow the migration of plant species, or it might migrate deep in soil, or there might also be redistribution of microorganism. In some cases, the microbial community composition changes and the new species emerge as dominant. Such changes in microbial communities affect not only soil carbon balance but also functioning and survival of plants. Changes in microbial community might also play some role in controlling the plant community structure and its resistance to disturbances and resilience (Classen et al. 2015).

5.4 Nitrogen Cycle and Microorganisms

Nitrogen reserves are available in abundance in air, in rock deposits and from living and dead organic matter. It is an important element required for synthesis of cellular components for all living beings. Nitrogen cannot be utilized directly by plants in its atmospheric form, hence requiring a more reactive form of nitrogen (Buresh et al. 1980).

The nitrogen cycle is one of the most important biogeochemical cycles on earth. It cycles the flow of nitrogen from atmosphere into ecosystems, both marine and terrestrial, through nitrogen fixation and finally returned to the atmosphere through denitrification (Wan et al. 2005). The fixed nitrogen is subsequently converted into a wide range of proteins and nucleic acids and oxidized compounds by microbes (Arnone 1999; Wan et al. 2016). Nitrogen cycle involves six distinct processes, mediated by microbes that proceed in an orderly fashion. Various processes like nitrogen fixation, nitrification, assimilation, ammonification and denitrification form the whole nitrogen cycle (Pajares and Bohannan 2016). Figure 5.2 shows details of nitrogen cycle.

Nitrogen fixation may be natural or industrial. In the natural process, nitrogen-fixing bacteria play a major role in nitrogen cycle as about 90% of nitrogen fixation happens due to them (Hu et al. 2016). These microbes are divided majorly into two groups. First, a symbiotic species that use root nodules of selective plants to live, mainly legumes, for example, *Rhizobium*, *Frankia* and certain species of *Azospirillum*. The second species live without host and freely and are found in soil systems and aquatic biomes, for example, *Cyanobacteria*: *Anabaena*, *Nostoc*,

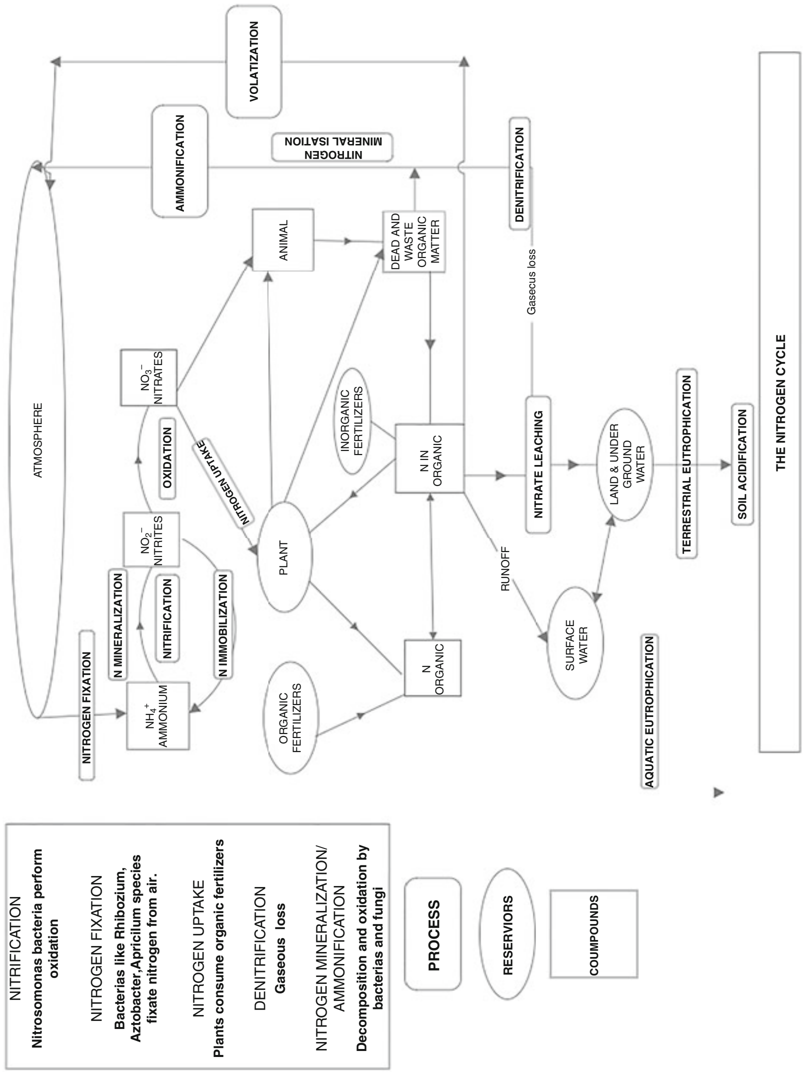

Fig. 5.2 The biogeochemical cycle of nitrogen

Azotobacter, etc. (Allison and Treseder 2008). Nitrogen fixation and nitrification are the processes leading to the formation of nitrate and ammonia. Nitrogen in the form of nitrate and ammonia is utilized by the plants and animals and the process is called assimilation. Plants absorb nitrogen through their roots and integrate them as proteins and nucleic acids. Animal use these by eating plants (Barnard et al. 2005a, b). Ammonification is the process where the organic nitrogen formed in the process of assimilation is converted into ammonia and hence becomes available for further nitrification and assimilation (Manning and Tiedemann 1995).

Nitrification is the biological conversion of ammonia to nitrate nitrogen. This usually takes place in two steps. In the first step, the microbes called *Nitrosomonas* convert ammonia and ammonium to nitrate, and then in the second step, the microbes called *Nitrobacter* convert nitrite to nitrate. The process is very rapid as these bacteria are aerobic and require dissolved oxygen of 1.0 mg/L or more for conversion. Denitrification is an anaerobic process in which nitrates are biologically reduced to nitrogen gas and released in air. The facultative and heterotrophic microbes are required for the process. This process occurs when oxygen is almost depleted (less than 0.5 mg/L). Nitrates act as oxygen source, are broken to gain oxygen and are converted to nitrous oxide released into air (Jiang et al. 2019).

5.4.1 Effect of Human Activities on Nitrogen Cycle

Anthropogenic activities have influenced the nitrogen cycle. Alteration in available nitrogen for plants has limited the growth of the plants as well as decreases its nutrient content in some region, mainly temperate and boreal. This problem is resolved by applying fertilizers into soil, which had initially increased the production of crops and plants. However, the bulk (80%) of N fertilizer applied in the field is washed off with run-off water or is lost as gas emissions and goes into the environment. At present, industrial fertilizers play a major role in providing nutrients to crop plants and about 50% food production depends on them. Use of industrial fertilizers and legume cultivation has increased the nitrogen addition to the environment to double. These increased quantities of plants sequestered the atmospheric carbon into the system and are believed to be the only positive effect of human activities on nitrogen cycle (Rakshit et al. 2012). The dumping of nitrogen especially in the form of fertilizers has led to the build-up of reactive N species in the environment and can have a toxic effect on humans as well as plants and animals. Thus, it is important to understand the various processes of nitrogen cycle so that agricultural practices can be improved, thereby minimizing detrimental effect of dumping of N in environment (Wallenstein and Hall 2012).

5.4.2 Effect of Enhanced CO_2 on N Cycle Microorganisms

In the process of plant growth and species diversity, CO_2 plays a crucial role. Studies reveal that rise in atmospheric CO_2 concentration has led to increased carbon from the atmosphere into the plants (Nie et al. 2014). It also enhanced the carbon content into the soil through rhizodeposition, leading to an increase in the organic matter content of soil. This would lead to further carbon sequestering causing simultaneous increase in nitrogen sequestration. Sequestered nitrogen will not be available for plant absorption and hence will gradually limit the plant productivity in terrestrial ecosystem (Hoosbeek et al. 2004). However, some studies also reveal that the soil carbon is not affected by change in CO_2 despite higher C inputs (Jensen et al. 2003). The impact of rising CO_2 is hard to predict without a good knowledge of interaction between carbon (C) and nitrogen (N) cycles (Phillips et al. 2012; Zang et al. 2015). There have been cases in which CO_2 has been responsible for enhanced N retention and decrease in leaching of nitrates and denitrification process (Phillips et al. 2006, 2009). In some other cases, increase in CO_2 has enhanced the process of leaching of nitrates and denitrification (Phillips et al. 2006). This increased CO_2 also increases the length and density of roots of the plants, hence also improving the N intake (nitrate and ammonium) of plants (Barnard et al. 2005a; Castro et al. 2010; Das and Mangwani 2015) and altering the N pool in soils (Björsne et al. 2014). N cycle processes like nitrification and denitrification are influenced by elevated CO_2 concentrations and in turn impact inorganic N concentrations in soil, leaching of nitrate and emission of N_2O (Cantarel et al. 2011; De Vries and Shade 2013). It is also important to understand the effect of elevated CO_2 on microbial N biomass because N immobilization in microbial biomass can have impact on plant productivity especially in N-limited ecosystems (De Vries and Shade 2013). Elevated CO_2 may have a good effect or no effect on soil microbial biomass of N. Change in microbial biomass is seen due to addition of fertilizers and hence the fertilizer-free soil has microbes insensitive to elevated CO_2 (Hartwig et al. 2002; Nowak et al. 2004; Fuchslueger et al. 2014). Studies also reveal that elevation in CO_2 is also responsible for increased root exudation which leads to more N immobilized in microbial biomass (Touceda-González et al. 2017). When the demand for N increases by heterotrophic bacteria, it tends to decrease the ammonium availability for nitrifiers and availability of soil nitrates (Cao et al. 2016). Root exudation results in mineralization of N as microbial cells and ammonium content in the soil increase (Paterson et al. 1997). Increased rate of mineralization can also promote nitrification and as a result soil nitrate concentration is modified (Zheng et al. 2008). Water availability is also affected by change in CO_2 concentration due to decrease in the rate of passage of CO_2 entering, or water vapour exiting from plants, also known as stomatal conductance. When this occurs for long period, it results in increase in denitrification process and loss in N reserves of soil (Zheng et al. 2008).

Due to human intervention and plants grown in fields, agricultural soils have a huge impact on global carbon and nitrogen cycles. For example, emission of nitrous oxide increases tenfold in cultivated soils as compared with conventional tillage practices (Robertson et al. 2000). From an agricultural viewpoint, elevated CO_2 concentration can alter the crop productivity and sustainability by improving N-use efficiency (Gamper et al. 2004; Nowak et al. 2004; Chen et al. 2017a, b). Due to increased CO_2, increase in fungal abundance and diversity has been observed in semi-arid regions. In dryland agricultural systems, the N cycle processes continue even under dry conditions, and the low N content of soil is the limitation for N availability (Schimel 2018; Li et al. 2020).

5.4.3 Effect of Enhanced Temperature on N Cycle

Microbial growth and enzyme activity are influenced by changes in temperature. Thus, change in temperature affects physiological processes like mineralization rate, growth of plants especially roots, diversity of plants and their distribution. Water occupies 70–90% of cell mass of microbes. Due to the warming and fluctuations in water level, it affects the soil microbial community in arid and semi-arid ecosystems. Warming induces water stress in soil microorganism and reduces their biomass. It is also responsible for decrease in the growth of plants which hugely impact the growth of soil microbes following which the nutrient content is reduced significantly (Pendall et al. 2004; Abbasi and Müller 2011; Xu et al. 2019). Impact of nitrogen on soil microbial communities also depends on water, as water and nitrogen have collective impact on microbes of nitrogen cycle. Higher water availability can improve the response of N cycle microbes. This is more prominently seen in temperate grasslands as water is limited in such ecosystems. In a case study, it is revealed that annual precipitation can drastically modify warming effects on microbe's community soil fungi in soil of meadows–steppe (Eckersten et al. 2001; Arcand et al. 2013). The microbes were stimulated by N addition or warming only in the presence of water and showed no response in the absence of it. This proves that water is primarily a limiting factor, and the warming effect of the functioning of microbes is dependent on the amount of water available (Kool et al. 2011; Rütting and Andresen 2015). Water stresses offer a very adverse growing condition and hinder activities in most organisms (Diao et al. 2020; Lafuente et al. 2020). Soil microbes constantly undergo a water stress environment and may get better adapted to drought environment. Hence, they become resistant to water stress. In semi-arid and steep desert sites soil microbes do not respond to warming much. Also, if microbes are not killed in the process of increased warming, it is seen that microorganisms lead to higher enzyme activities and increase in assimilation of nutrients (Chen et al. 2017a, b; Zhang et al. 2017). With the advancing world, high-latitude biomes, such as boreal and temperate ecosystems, experience the swiftest rates of impact of warming due to increased emission of harmful greenhouse gases. The impact of warming is also seen in snow-prone areas (Magill et al. 2000; Garrett et al. 2006; Caldwell et al. 2007; Butterly et al. 2015).

Microbial taxa show resistance to climate change conditions such as warming (Zak et al. 2011; Eldridge et al. 2020). Wood decay fungi which decompose the components of dead plants, such as cellulose, hemicellulose and lignin, have higher sensitivity to changes in temperature (Ainsworth and Long 2005; Choi et al. 2005; Maestre et al. 2013). Mycorrhizal fungi which live in living plant roots, exchanging nutrients from plant to soil, are comparatively less sensitive and can have both positive and negative responses to rise in temperature depending upon how this influences the soil and plant factors like nutrient and moisture present in soil and physiology of plants (Iversen 2010). Decomposition rate of microbes also increases with warming resulting in more soil carbon content (Garcia et al. 2020).

In snow-free months of a year, increases in carbon and nitrogen concentration take place as organic matters of soil decompose. But these effects tend to reduce during winter months under the increased freeze and thaw. It is also found that increase in freeze and thaw cycle disturbs the microbial plant interaction in N cycle processes and inorganic N availability is enhanced. Like warming, few microbial taxa can acclimate to freezing conditions. Different species have different levels of tolerance towards freezing. Since there are multiple functional groups of microbes involved in various processes of N cycle, like decomposition, nitrification and denitrification, it is hard to predict the behaviour of overall functional groups in the influence of change in climate (Yergeau and Kowalchuk 2008; Dooley and Treseder 2012). Most of the studies conducted are on biomes from artic, boreal or temperate regions as they usually have more impact from global climatic change like increase in temperature at higher elevation (French et al. 2009; Wan et al. 2016). A study on shrub land ecosystems has showed that there is an increase in soil respiration due to warming (French et al. 2009).

A high variability of mineralization of N is observed under the influence of warming. But as there is a lack of direct connection among temperature and N mineralization, the occurrence of processes on nitrogen cycle is terribly slow and has little impact on the N cycle. The influence of temperature on soil respiration controls carbon balance more in the short term rather than N mineralization controlled by water. In extreme temperature as N mineralization becomes unresponsive due to lack or excess of water, this promotes the N limitation process impacting both plant and microbial growth and also limits carbon sequestering as mentioned before. Higher increase in temperature may influence the soil moisture impacting the water-dependent process of N mineralization which would further cause increased N leaching and C sequestration.

Warming induces stress in microbial communities under various biogeochemical cycling; thus, there are physiological trade-offs and there is reallocation of resources in between growth and survival mechanisms. During growth seasons, the composition of soil microbial community tends to move towards fast-growing species that use less carbon (CO_2). These species are decomposers of cellulose and polysaccharides from plants as C sources and release CO_2 in huge amount in the atmosphere. Microbial activity may also decline with the drop in soil moisture as the growth of microbes is dependent on moisture availability. Higher temperature during growing season and freeze–thaw cycles of winter combined together negatively impact the biogeochemical cycles, by decreasing the amount of extractable organic C and N in soils. Moreover, a reduction in enzyme activities, respiration and biomass of microbes is also seen. A compounded suppression under stressful temperature conditions can occur, if there is biomass decrease in active microbes or if they exchange their traits which help them decompose with traits allowing them to adapt to temperature fluctuations. The traits which allow them to be more tolerant in these stress conditions include dehydration capacity, osmolyte production, thick cell walls and shock resistance proteins, C-storage vesicles. In the coming years, high grassland ecosystems are going to face more temperature rise, and by 2100 the temperature is going to rise by 3–8 °C.

5.4.4 Effect of Drought and Increased Precipitation on N Cycle

Droughts or lack of precipitation causes immense stresses in all living organisms especially soil microbes. Sometimes, droughts or lack of precipitation is also responsible for making them extinct (Fierer et al. 2005). The presence or lack of water plays an important role in physiology of plant communities and in regulating soil microbial activities. Drought and wet–dry cycles create immense challenge and bring out physiological stress in microbes as microbial population vitality and composition are altered by various factors like reduction in water and nutrient due to warming. Soil microbes have tendency to adapt to their immediate surrounding by undergoing osmosis when stressed due to drought, in the process of which they tend to retain water in their cells as the surrounding dries up. Fungi, although more drought-prone than bacteria, were found to be more repressed than bacteria in a study of grassland ecosystem. This was seen mainly due to increase in salinity and alkalinity of soil present as this change favours fungi growth. Also bacteria tend to be better at tolerating high salt concentrations and hence are more resistant to drought caused by warming (Niklaus et al. 2001; Bai et al. 2013). Other studies have revealed that microbes have positive reaction in response to increase in nitrogen when there is availability of water or lack of water stress; hence, this shows that although nitrogen have power of limiting the growth of microbes, its effects are highly dependent on change in precipitation. Increase in precipitation can incorporate nitrogen in soil and enhance the enzyme activities of microbes as water is necessary for nutrient distribution and renewal of soil (Rengel and Marschner 2005; Wan et al. 2016). Precipitation tends to release the microbes from there tensed state in drought conditions by replenishing the soil with resources. Hence, precipitation and drought take place alternatively.

The effect of drought can be seen on both nitrogen and carbon cycles although the impact is different. Mineralization increases in nitrogen cycle as the dry soil is wetted due to precipitation. The rewetted soils are rich in nitrogen and fuel the re-growing microbes with excess nitrogen, leading to nitrogen mineralization. Bacterial osmolytes and dead microbes are responsible for nitrogen-rich substrates that enhance the nitrogen content in soil. Fungi produce trehalose and polyols, which are nitrogen-free osmolytes that hinder the mobilization on rewetting (Robertson et al. 2000; Garrett et al. 2006; Butterly et al. 2015). Nitrification is sensitive to drought conditions, and the available ammonia is constrained in dry soils, but with the occurrence of precipitation, the rewetted soil generates a mass of nitrogen, showing a saturated state in the soil surrounding. In dry soil, ammonia is the dominant form of nitrogen, but post rewetting, a swift increase in nitrification is seen which allows a flux of nitrogen in gaseous form. Hence, drying–rewetting changing aspects appear to have disproportional effects on nitrogen losses (Ainsworth and Long 2005; Zak et al. 2011; Delgado-Baquerizo et al. 2013; Eldridge et al. 2020).

Drylands (arid, semi-arid and dry–subhumid ecosystems) provide ecosystem services like cattle raising and wool, meat and food production. Due to prevalent dry conditions, these ecosystems are more vulnerable to climate change. The change in precipitation and temperature rise has encouraged expansion of dryland and is expected to cover 10% of earth's surface by the end of this century (Smucker et al. 2007; Dong et al. 2010; Mueller et al. 2015). In these ecosystems, soils are generally deficient in nutrients; thus, nitrogen concentration plays an important role in determining net primary production and decomposition of organic matter. Dryland ecosystems are major contributor for gaseous N emissions and account for 30% of global emissions. Surface soil communities of drylands are comprised of mosses, lichens and cyanobacteria as they occupy open spaces between plant canopies (Gruza et al. 1999; McMichael et al. 2006; Rajkumar et al. 2013). Water availability is considered as an important parameter along with temperature for N cycle microbial-mediated processes. The various processes of N biogeochemical cycle like N fixation, production of dissolved organic N, nitrification and emission of gases are mediated and influenced by microbes growing in dryland soils.

5.4.5 *Effect of Extreme Weather Events on N Cycle Microorganisms*

Extreme weather events like waterlogging and extreme droughts put a severe impact on biomes by changing patterns of water availability to plants and microbial communities and also the physiochemical properties of soil. Changes in soil structure and pH brought by these weather events affect the availability of soil nutrients and cause changes in microbially mediated processes in biogeochemical cycles (Rosenzweig et al. 2001; Kumar et al. 2003; Coelho et al. 2013). According to recent researches, the community and functions of microbes show variable response to varying weather phenomena. Microbial community might be resistant to the various changes brought out by extreme weather events, and the ecosystem functioning is not believed to be affected by community changes in microbes. It is important to understand the microbial responses in terms of both community and functioning as these play a major role in the working of nutrient cycles and their sinking and pooling of the nutrient compounds (Zepp et al. 2007; Bowker et al.

2011; Castillo-Monroy et al. 2011). Along with weather events like drought and floods, one extreme weather event is wildfires or fire in general. Wildfire caused by extreme dry weather or any other anthropogenic activities also impacts the N cycle processes channelized by microbes. Severe fire tends to modify the properties of soil such as its biological, physical and chemical parameters, depending on temperature peak and its duration and soil's initial conditions, and negatively impacts the soil microbes too. Ash accumulated post fire changes the pH of soil and nitrogen gets volatized at temperature above 200 °C (Neary et al. 1999; Dooley and Treseder 2012). Nutrient availability is equally impacted and stays affected for many years post fire destruction. In some researches, it is also seen that N mineralization actually increases initially, increasing the inorganic N content in soil, but then tends to decrease approx. after 6 months into its original state. N mobilizes, causing leaching of nitrite oxide (NO^{3-}) through soil later post any fire event (Moreno-Jiménez et al. 2020).

5.5 Conclusions

Microbial processes associated with biogeochemical cycles play an important role in global fluxes of key greenhouse gases like CO_2, CH_4 and N_2O. These microbial processes are influenced greatly by climate change. These changes can be either positive (increased cell biomass and/or enhanced physiological functioning) or negative (decreased cell biomass/or reduced physiological functioning). Depending upon the response of the microorganisms, they either can help in maintaining the ecological balance and mitigating the effect of climate change or can aggravate the problem. Thus, it is necessary to study the changes caused due to climate change on microbial processes associated with biogeochemical cycles. This aspect must be incorporated in the models predicting the impact of climate change and mitigation measures, only then the results will be more realistic and meaningful. Most of the studies conducted have taken into account the effect of one factor. However, in nature, all the physical factors exert their influence at any given point of time. Thus, it is necessary to conduct more studies that mimic natural conditions as much as possible as the interactive effect of various climatic factors will be different from single factor effect. Moreover, due to climate change, incidences of extreme weather events have increased, but very few studies have been conducted in this direction. Thus, future studies should also take into the account the effect of extreme weather event.

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