Chapter 2
Climate Change Alters Microbial Communities

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Abstract Microbial communities are key players in regulating ecosystem processes. Climate change factors such as CO_2 and temperature alter the microbial composition which in turn influenced the activities of microbial communities in the ecosystem's settings. As a result of their activities in the ecosystems and their resultant effect, changes to climate do occur. The effects of global warming, extreme weather conditions and other biotic and abiotic factors on microbial community functioning and richness still remain unclear. The present study aimed to review the influential roles of climate change on structural composition and functionality of microbiomes in their ecological niche. We also discussed the impacts of climate change on microbial environments and how microbial communities are capable of responding to extreme climate changes. It is believed that knowledge of the interaction of climate change and microbiomes, including their adaptation, would play a major role in mitigation and combating of climate changes in different ways.

Keywords Climate change · Microbial communities · Ecosystems' sustainability · Global warming · Niche · Mitigation · Alterations

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2.1 Introduction

Microbial communities are ubiquitous in nature and the major contributors and mediators of biogeochemical cycles and sustainability of the earth. As a result, they have great influence on the ecosystem and climate. That notwithstanding, climate changes affect microbial diversity either directly or indirectly (Nie et al. 2013). Microbial communities develop survival strategies in order to adapt to changes in climate, which increases their chances of survival in any ecosystems. Survival strategies by these microorganisms could be an alteration in microbial community (i.e. outcompeting of other species and primary succession of new species) or sudden changes in the physiology of individual species (Fierer et al. 2007; Philippot et al. 2010; Placella et al. 2012; Zimmerman et al. 2013).

Alteration in microbial community influenced changes of ecological features of microbial communities (Kvitek et al. 2008; Wang et al. 2011). For instance, microbes that have experienced harsh drought and rewetting during rainy season have higher chances of becoming more resistant in this type of unfavourable conditions than microbial species that are inexperienced to climate change challenges (Fierer et al. 2003; Bouskill et al. 2013; Evans and Wallenstein 2014). The composition of microbial communities in soil is very diverse, making them exposed to all sort of climate change factors such as high temperature, moisture fluctuations and nutrient availability (Bardgett and van der Putten 2014).

The variation in the functions and structures of the ecosphere leads to major climate changes like floods, drought, greenhouse gas emissions, ozone depletion and heat waves (Smith 2011; Reichstein et al. 2013). These have consequential effect on resistance and resilience of different microorganisms and their ability to recover from ecological changes that could have negative effects (Nimmo et al. 2015; Oliver et al. 2015; Ingrisch and Bahn 2018). Studies on climate changes in relation with alterations of microbial communities, especially the impact of climate changes in the transition of microbial diversity and population, are still limited. Therefore, there is need for holistic understanding of climate changes, and we need to understand their effect on microbial community variability, diversity and contributions as well as impacts of these microbial alterations to the ecosystems. The motivation behind this chapter is to shed light on the effects of climate change on microbial community composition and functions. We discussed adaptations of microbial communities to such effects.

2.1.1 Extreme Effects of Climate Change on Microbial Communities

Extreme conditions such as drought, high temperature and greenhouse gases can alter the structure of microbial distributions and growth in a specific ecological niche (Zhou et al. 2012). The microbial communities include virus, fungi, protista, archaea and bacteria that are inhabitants of different parts of ecosystems. These organisms play a vital role in carbon and nitrogen cycles which help in sustaining the ecosystem's processes (Bardgett and van der Putten 2014). Although studies on the transitional alteration of microbial communities are limited. proofs are beginning to unveil themselves that climate change could play a role in these transitions. Moreover, the reaction to transitional changes that occurred in microbial communities is unmeasurable. For instance, the reaction of soil microbial communities to greenhouse gas could either be positive or negative (Janus et al. 2005; Lipson et al. 2005, 2006; Lesaulnier et al. 2008; Austin et al. 2009). Furthermore, reduction in soil water retention, increase in carbon production and extreme drought could lead to alteration of microbial colonization of a particular habitat (Robinson et al. 2016).

Recent studies showed that drought serves as a key factor of climate change and has a stronger impact on bacterial community than fungi (Bapiri et al. 2010; Vries et al. 2012; Barnard et al. 2013; de Vries et al. 2018). The possible reason could be fungi hyphae penetrate deeper into soil profile for more access to water during drought. Therefore, they are able to resist drought condition than bacteria. Soil microbial community could also be altered in its functionality and compositions from their original state to a new transitional state when there is nutrient enrichment of a particular soil causing the elevated production of greenhouse gas especially CO_2 (Allison and Martiny 2008; Zhou et al. 2012; Leff et al. 2015). This effect could lead to increase in atmospheric CO_2 with concomitant occurrences of global warming. Then, the atmospheric CO_2 could also change the structure and composition of microbial communities and distributions in a given environment (Zhou et al. 2011).

Furthermore, a major trait for high resistivity to climate change had been traced back to fungi. This is characterized by high genomic potential. With this, they are able to withstand different forms of harsh conditions and weather (Egidi et al. 2019). Another important factor that also affects alteration of microbial community is nutrient availability. Nutrient availability also plays a very important role in microbial growth and population. Nutrient enrichment due to agricultural practices could have impacts on total mass of bacteria within a specific area and could bring about elevated population of bacteria (De Vries and Shade 2013; Bardgett and van der Putten 2014). Elevated population of bacteria affects the energy flow in the soil which have been connected with carbon and nitrogen cycling (Gordon et al. 2008; Vries et al. 2012).

2.1.2 Influence of Climate Change on Microbial Community's Functions and Compositions

2.1.2.1 Soil Microbial Communities

Soil microbial communities include all forms of microorganism found in the soil and terrestrial environments. The soil contains a large group of microbes making them the most complex diversified communities on earth (Flemming and Wuertz 2019).

They mostly include soil pathogens, symbionts, mutualists, producers, decomposers etc. Soil microbes play an essential role in shaping and regulating the amount of organic carbon stored in soil which is released back to the atmosphere in the ecosystem (Singh et al. 2010; Bardgett and van der Putten 2014). Climate changes play a vital role in the alteration of soil microbiome diversity and also their interaction with other organisms especially with plant. Plant interaction with soil fungi (mycorrhizae) is involved in plants' acquisition of phosphorus and nitrogen (Fellbaum et al. 2012). Various studies have shown how various climate extremes such as drought, flood and ice impact on the soil microbes.

The activities and the metabolic processes that are been carried out by soil microbes are of paramount importance because they help balance the elemental and chemical compounds within the earth's crust (Singh et al. 2010). Climate changes on soil microbiomes could have a positive impact when soil microbes enhance plant performance, for example, biomass production, organic matter decomposition and survival as in the case of legumes and nitrogen-fixing bacteria (NFB), and it could lead to negative impact within the microbial communities and even to plant when their effects are pathogenic, greenhouse gas production (Smith 2011).

Most soil bacteria and archaea are the major facilitators of biogeochemical cycling of essential elements such as nitrogen and carbon (de Vries et al. 2018). Organic matter decomposition is carried by soil fungi and bacteria, which plays a major role in carbon cycle and release of CO_2 into the atmosphere. Another important role played by soil microbes is the fixing of nitrogen by nitrogen-fixing bacteria (NFB) in the soil and plant during mutualistic relationship with leguminous plants (Fig. 2.1) (Hurd et al. 2018).

2.1.2.2 Marine Microbial Communities

The earth itself is made up of 70% waterbodies. Climatic factors such as temperatures affect the rate of biological and metabolic process, nutrient availability and marine microbiome dispersal (Jørgensen and Boetius 2007). Negative consequences of climate change such as shift in marine food webs and carbon export buried into the sea bed have been associated with the increase of greenhouse gas concentration on ocean acidification, nutrient supply, temperature and irradiation (Gao et al. 2012; Rintoul et al. 2018; Hurd et al. 2018). Marine phytoplanktons like cyanobacteria and algae are important in marine food chain and have been found out to perform half of the global photosynthesis CO_2 fixation and half of the oxygen production (Behrenfeld et al. 2016). Apart from marine phytoplanktons, chemolithoautotrophic (Fig. 2.1), marine archaea and bacteria could fix CO_2 under dark conditions in deep ocean waters (Pachiadaki et al. 2017). Cycling of elements is also contributed by marine archaea and bacteria (Bunse et al. 2016). A group of cyanobacteria known as *Prochlorococcus* and *Synechococcus* are very abundant photosynthetic microbes in the ocean that removed about 10 billion tons of carbon each year which is about

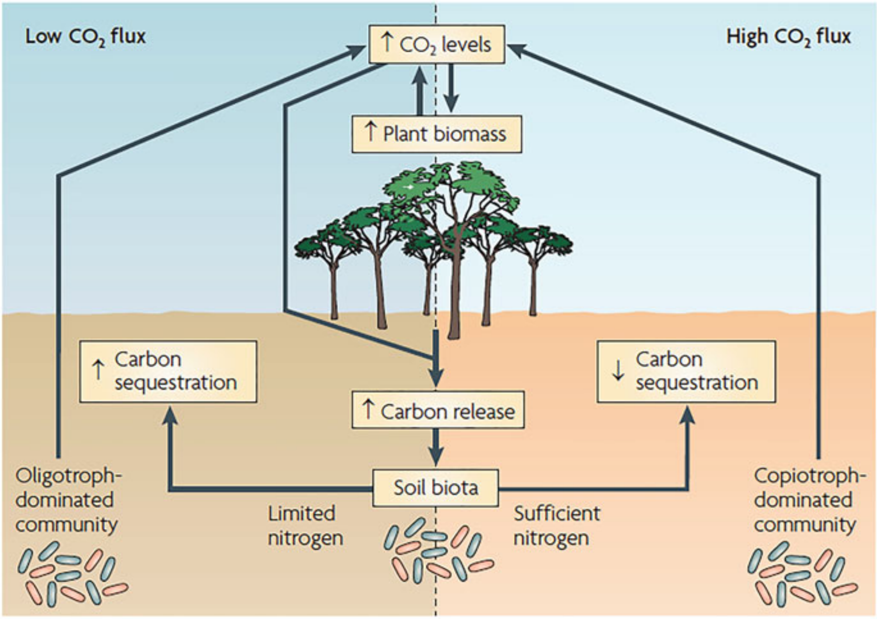

Fig. 2.1 A simple concept model illustrating the complex feedbacks climate change causes. Increased carbon dioxide (CO_2) levels resulting in a higher plant biomass and a higher carbon rhizodeposition, thereby increasing microbial biomass and activity in the short term. However, mineral nutrient limitation such as nitrogen may constrain this response in the long term. Such mineral limitation will affect oligotrophic and copiotrophic microorganism dominance in a given ecosystem, which in turn may influence the flux of CO_2 (with permission from Singh et al. (2010))

two-thirds of carbon fixation in ocean (Blount et al. 2008; Mariadassou et al. 2015; Youssef et al. 2015).

Thermal and latitudinal gradients and oceanic current are important factors for marine microbiome distributions (Wilkins et al. 2013; Cavicchioli 2015). These distributions could be affected by low pH which may lead marine archaea and bacteria to alter their gene expression to support cell maintenance (Bunse et al. 2016). Moreover, environmental and other factors influence the overall response and activities of marine microbes. For instance, reduction in cellular ribosomal concentration and increase in synthesis of protein in eukaryotic phytoplanktons occur in the presence of elevated temperature (Toseland et al. 2013).

2.1.3 Adaptation of Microbial Communities to Climate Change

Due to harmful environmental climate conditions, microorganisms have devised so many ways to adapt to unfavourable changes. These adaptations could be direct adaptation, which involves structural and functional changes of their organelles or metabolisms, or indirect adaptation, which involves changes of their environments to suit their habitation. For instance, the presence of high content of peptidoglycan and the ability to form spores make gram-positive bacteria to withstand unfavourable drought conditions than gram-negative bacteria (Potts 1994). Researches from 2013 to 2016 had shown that the population of gram-positive bacteria such as *Actinobacteria*, *Firmicutes* and *Chloroflexi* elevated more than that of gram-negative bacteria such as *Proteobacteria*, *Acidobacteria* and *Verrucomicrobia*. Osmotic stress was observed to play a role due to the fact that in 2015 it was rainier (Cruz-Martínez et al. 2012). The same gram-positive bacteria had been found to contain genes for producing amino sugar, alcohol and simple carbohydrate metabolic pathways which help them to tolerate stress (Borken and Matzner 2009).

Enzymatic activity is another approach used by microorganisms to survive harsh conditions. As we know, most metabolic reactions occur in the presence of enzymes. Therefore, enzyme productions could be increased by allocating more nutrients to their production in maintenance of the microbes (Wang et al. 2011). Enzymatic activity is very important for microbial survival in the ecosystems. This is because some enzyme production has been triggered when certain extreme climate changes occur such as high temperature or low moisture. For instance, bacteria produce spore to prevent desiccation during low moisture condition. Production of these spores is done with the activation of inert enzymes that help bacteria to survive unfavourable conditions. Despite all these, temperature and moisture fluctuation have impacts on enzyme productions and activities (Allison and Vitousek 2005).

Bacteria use two strategies for survival. The first is copiotrophic strategies involving the use of low resources or nutrients efficiently but with high growth which enable them to recover quickly from unfavourable conditions (resilience). The second is known as oligotrophic strategies that utilize high nutrients efficiently but have low growth rates making them to withstand unfavourable conditions (resistance) (Fierer et al. 2007; De Vries and Shade 2013). 'Ecological networking' has been shown as another approach that the microbial community could use for survival. This ecological networking involves interaction of a particular species with another which could affect their response to unconducive climate change (de Vries et al. 2018; Ramirez et al. 2018). Finally, some microbial community are known to possess 'traits'. These traits give them a special feature for survival during climate change. Some of these traits include dormancy genes (resuscitation promoting factors and sporulation) and operon count (Nemergut et al. 2016; Kearns and Shade 2018).

2.2 Contributors of Climate Change and Their Impacts on Microbial Community

2.2.1 Temperature

Temperature is one of the top contributors affecting the rate of metabolisms. Temperature plays a critical role for the success of metabolic processes. Instability of temperature in microbial metabolisms could bring about transitional alterations to the microbial community compositions. Moreover, high temperature contributes to the emission of atmospheric greenhouse gases that affect the survival of microbial community in many environmental settings (Fig. 2.2). Atmospheric greenhouse gas increments could be brought about by metabolic functionality changes in decomposers due to increase in temperature (Schindlbacher et al. 2011).

However, fungi play a crucial role in degradation of organic matters in the absence of nitrogen content in the soil, and temperature could cause warming which affects the amount of high nitrogen in the soil. Occurrence of this situation affects the activities of nitrogen bacteria such as nitrifying bacteria as they oxidize nitrogen and other nitrogen compounds due to high temperature that support their metabolism. Fungal decomposition is not only affected by sudden changes in the temperature but is also affected by other microbes that decompose organic matters and their diversity. Microbial community in water is also known to be affected by temperature change. High temperature change does not only affect their diversity or growth, but also it affects their metabolisms, population and resistivity. Algae species distribution all over the marine water bodies in the world especially the cyanobacteria is being affected by temperature (Beardall and Raven 2004). In the present twenty-first century, scientists have estimated that there may be continues temperature rise of surface of marine waters caused by global warming (Sarmento

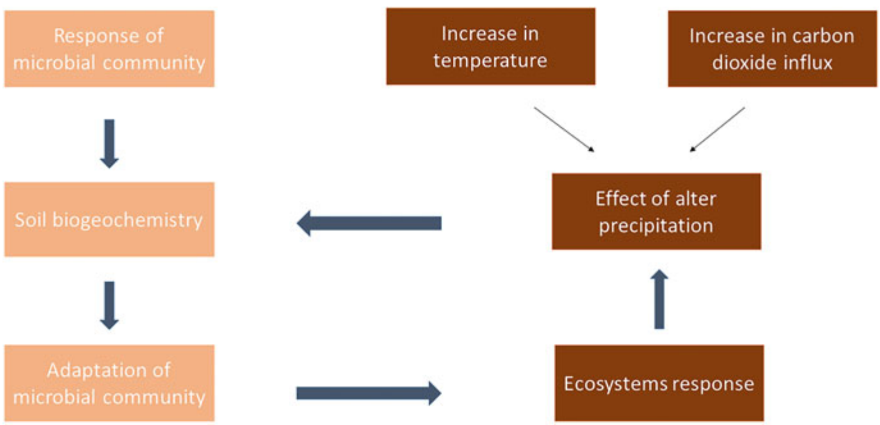

Fig. 2.2 An illustration of the interactions of climate change and some ecological factors that drives changes in microbial communities

et al. 2010). Therefore, increase in temperature could bring about negative impact on water chemistry which in turn influences microbial diversity, growth and populations (The USGS water science school 2015).

2.2.2 Water Content

Water is indispensable means of sustenance and functionality for all forms of life. Microbial community needs water to carry out their day-to-day metabolism and activities. The absence or availability of water affects the alteration or changes of microbes in the ecological systems. Microbial activities and composition are being affected by the presence of water. Furthermore, it stimulates these microbes to respond to soil respiration in regard to moisture and temperature (Aanderud et al. 2011). Changes in moisture content of terrestrial and soil niches determine the nature of microbial community in a particular ecological niche and also decomposition of organic materials (Fierer et al. 2003; Singh et al. 2010). The most intense consequence of different climate changes or any other forms of climate extremes on fungi, bacteria and any other microbial community is much higher when there is an alteration in water precipitation (Fig. 2.2). Therefore, increase or decrease in water precipitation regulates the microbial community of the ecosystem, their functions and structures and most importantly their metabolic processes (Schimel et al. 1999; Williams 2007; Castro et al. 2010).

Microbial activities could also be suppressed in environments such as soil and saltwater when there is low water availability and reduced enzymatic activity and hydration in the microbes. CO_2 emissions and productions to the atmosphere and the ecosphere could also be affected by soil moisture as it regulates soil respiration (Aanderud et al. 2011). Change in moisture and ecological factors is crucial for microbial lives, and processes depend on the regulation of these ecological factors (Smith et al. 2008).

2.2.3 Plant

Plant interaction with microbial community has been observed as the factor that alters microbial community diversity. One of the mechanisms is the distribution of plant–root absorbed carbon to soil microbial communities when plants are responding to climate changes. For instance, during dry weather conditions, there is reduction of photosynthetic processes due to the absence of water required for photosynthesis. This in turn reduces carbon allocation to soil microbes from plant which will result in low substrate for these microorganisms to carry out metabolisms. Fungi living in mutualistic association with plants are normally affected, for example, *mycorrhizae* (Hasibeder et al. 2015; Canarini and Dijkstra 2015; Fuchslueger et al. 2016; Bakhshandeh et al. 2019; Chomel et al. 2019).

Furthermore, bacteria community in the soil could also be affected by plant activities. Carbon emissions by plants to soil bacteria during rainy season increase population and growth of these microbes. Plant–soil relationship is able to be sustained by these bacteria due to the activities that they carry out in the soil such as soil organic matter decomposition or degradation, plant–microbial mutualistic relationships (nitrifying bacteria in legume) and oxidation of toxic compounds to nontoxic compounds which the plant could absorb and utilize (Karlowsky et al. 2018). Bacteria soil community could increase its size when there is increase in microbial activities and respiration which support decomposition of soil organic carbon. Drought-induced changes may trigger this process especially in the root exudates of plants (Chomel et al. 2019).

Plant association with soil microbes especially with fungi (*mycorrhizae*) and some mutualistic bacteria is a very important factor that needs to be studied as it affects alterations or transitions of microbial communities in the soil. Studies have shown that these mutualistic relationships could support some microbes living on a drought-tolerant plant where they could derive water, shelter and nutrients. Also, plant types and compositions could affect microbial community from recovery due to drought when there is low moisture content in the soil. These could cause nitrogen competition between plants and microbes (Orwin and Wardle 2005; Bloor and Bardgett 2012). Therefore, more researches should continue to be conducted in this area to understand plant interaction with microbes, their impacts on each other, their roles in climate changes and influence of plant alteration to microbial diversity.

2.3 Alteration of Microbial Community due to Climate Change in Other Aspects

2.3.1 Agriculture

Agriculture cannot be fully discussed without mentioning the roles of microorganisms. Microorganisms play an important role in the development and sustainability of crop growth and development as well as animal productions. Agriculture practices and methods and farmer activities also have an impact on microbial diversity (Table 2.1) and the ecosystem as well. Fertilizer applications have really contributed to the pollution of the environments, increase in nitrogen and distortion of biogeochemical cycles leading to threatening of the ecosystem (Steffen et al. 2015; Greaver et al. 2016). Microorganisms' oxidation and reduction of nitrogen compounds especially N_2O have made the agriculture sector as the highest emitter of greenhouse gas. Nitrogenous transformations such as ammonification, nitrification, nitrogen fixation and denitrification are different ways in which N_2O gas could be released into the atmosphere by these microbial communities (Greaver et al. 2016). Moreover, fertilizer applications could bring about microbial competitions and diversity.

Table 2.1 Environmental change transmission parameters and diseases (Eisenberg et al. 2007)

Environmental change	Description	Disease
Hospitalization	Increased people and time spent in hospitals	Tuberculosis (TB) Enteric and respiratory diseases
Urbanization	Increasing migration to and growth within towns	Diseases caused by faecal–oral pathogens Diseases caused by TB
Antibiotic usage	Emergence of antibiotic-resistant strains of bacterial pathogens	Multidrug-resistant TB and salmonellosis *Salmonella typhimurium*
Water projects	Water flow changes due to dam construction and irrigation networks	Schistosomiasis Malaria
Agricultural intensification	Changing crop and animal management practices; fertilizer and biocide use; use of genetically modified organisms	Cryptosporidiosis Diseases caused by *E. coli*
	Increased interplay between humans and domesticated animals	Influenza, severe acute respiratory syndrome (SARS), avian flu
Deforestation	Loss of forest cover, changing water flow patterns, reforestation and human encroachment along and into forested areas	Malaria Lyme disease Haemorrhagic fever AIDS
Transportation project	Construction of roads, increasing access to remote areas	Malaria STDS
Natural perturbations	Large-scale climate and other changes such as El Niño events	Cholera and leptospirosis
Cataclysmic events	Localized landscape changes caused by earthquakes, tsunamis, large fires and others	Water-related diseases like cholera
Climate change	Changing temperature and precipitation	Malaria, dengue fever and schistosomiasis

For instance, soil enrichment with elemental nutrients could result to unwanted algae bloom (Posch et al. 2012).

Rice cultivation and farm ruminant animals as other aspects of agriculture have also played a significant role in climate change and microbial biodiversity. Based on data from the World Bank, agricultural land, it has been estimated that 40% of terrestrial land has been devoted for crop production and animal rearing (Lanz et al. 2018). Natural CH_4 emissions that contribute to global warming are released by agricultural practices. CH_4 emissions from ruminant animals are the largest single source of this gas with the help of microbial community of intestinal tract of ruminant animals (Ripple et al. 2014). A total of 20% of agricultural CH_4 emissions by rice paddling contributes to CH_4 greenhouse gas. Scientific prediction has shown that by the end of this century, they may be doubling of CH_4 emissions only from rice paddling and cultivation (Groenigen et al. 2013). Thus, there is an urgent need for more researches and studies on agricultural practices in relationship with microbial activities.

2.3.2 Infections

Susceptibility of vectors and pathogens could be due to climate changes (McIntyre et al. 2017). The dispersion of microbial vector-borne disease and their virulence factors depend on climate change (Table 2.1). Changes in the ecosystems could affect the functionality of human health and food availability in ways where these microbial communities especially fungal, bacteria and virus cannot adapt to abiotic and biotic factors (Giraud et al. 2017; Cavicchioli et al. 2019). Fluctuation of rainfall and temperature due to climate variability is strongly attributed to many communicable diseases such as vector-borne and waterborne diseases and other forms of diseases such as Zika virus disease, plague, cholera and many more (Bouma and Dye 1997; Baylis et al. 1999; Rohani 2009; Kreppel et al. 2014; Caminade et al. 2017). For instance, the distribution of dengue fever and malaria which are known to be climate dependent often shifts in response to climate change (Bhatt et al. 2013; Pecl et al. 2017). Shift in host response and parasite adaptation to host are health risks that could be caused by climate change (Raffel et al. 2013). Antibiotic resistance of human bacterial pathogen has been predicted that climate change could also be another contributing factor (MacFadden et al. 2018).

Lower salinity and high temperature in estuaries' habitat caused by increase in precipitation could be associated with the spread of *Vibrio cholerae* infections which promote their growth. This has been observed in Bangladesh, Baltic Sea Region, North Atlanta and North Sea including human pathogen of *Vibrio* spp. (Pascual et al. 2000; Baker-Austin et al. 2013; Vezzulli et al. 2016). Transport and introduction of pathogens are influenced by effects of weather dispersal, and growth of the environmental conditions contributes to the spread and emergence of diseases (Bebber et al. 2013). Global environmental changes on pathogens, ecology of pathogens and host relationships with pathogens are basic knowledge that must be understood for strategic and effective control and spread of diseases (Johnson et al. 2017).

2.4 Microbial Mitigation to Climate Change

To combat climate change, we need to understand microbial efficacy and functionality towards mitigation of climate change. These involve harnessing of microbial biochemical molecules and processes and inducing of advantageous genetic sequences or genes into a potential microbe. For instance, the roles of microbes in agriculture could be supported when fertilizers are used with reduced nitrification inhibitors. This will help support soil bacteria especially nitrifying bacteria to produce more nitrates for plants and prevent subsequent leaching. Another approach could be the use of considerable amount of fertilizers which will reduce the availability of elemental nitrogen to soil microbes and less production of nitrous oxide. This will help reduce the impact of global warming (Smith et al. 2008). Carbon sequestration could be a very important approach in reducing atmospheric CO_2 (Prosser et al. 2007). Forest soils have been considered as effective for carbon stroage due to abundance of bacteria and fungi and favorable environmental conditions that support the growth of microbial communities (Bailey et al. 2002; De Deyn et al. 2008; Busse et al. 2009; Castro et al. 2010).

Methane flux emission is mostly caused by microbes. It is theoretically possible to control microbial activities in a considerable amount of CH_4 emissions from terrestrial ecosystem. Ninety percent of CH_4 emissions in the soil are oxidized by methanotrophs before escaping into the atmosphere (Tate et al. 2007; Smith et al. 2008). With these studies, rice cultivation has improved flood management and could reduce net emission of CH_4 by increasing oxygen availability in soils when methanotrophs absorb a proportion of the CH_4 produced. Also, quality feed and use of antibiotics, vaccines and other forms of electron acceptors are ways that could be employed to reduce methane emissions in ruminant animals (Smith et al. 2008).

The use of biochar could be a mitigation option in the treatment of climate change. Microbes play a role in breaking down organic matters that support the growth of plants. This organic matter decomposition by soil microbes could be mixed with biochar which will help in organic matter retention and preventing other microbes from carrying out ammonification and releasing of carbon (Weng et al. 2017). Finally, the use and development of non-greenhouse gas emission technologies and biotechnologies could be a lasting solution to global warming and climate change. These will surely solve the crisis of clean energy, clean water and industrial waste management treatment (Timmis et al. 2017).

2.5 Conclusion

The role of microbes in the ecosystem is of utmost importance in the regulation of the abiotic and biotic factors affecting the ecosystem. Microbial communities are the major regulators of all life processes and occurrence of the global climatic changes. Other factors also contribute to climate change such as human activities and industrial revolutions. These regulations could one way affect the alteration of microbial community and diversity. The alterations of these microbiomes could bring about positive or negative feedback to the environment and the ecosystem at large. The feedback could result in either direct impacts to the microbial community and other macro-organisms or indirect impacts to the environment. There is an urgent need for more researches to link climate change and microbial community and to understand the consequential impacts of transitions of microbial community after and before the processes do occur.

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