Chapter 11
Role of Fungi in Climate Change Abatement Through Carbon Sequestration

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11.1 Introduction

The United Nations Environment Programme and the World Metrological Organization established the Intergovernmental Panel on Climate Change (IPCC) in 1988. The aim of setting up IPCC was to evaluate technical, scientific, and socio-economic information related to climate change, the potential impact of climate change, and its possible mitigation measures. IPCC published a report in the year 2014 which made it clear that climate change is not a myth. To deal with climate change is a challenge for the worldwide scientific, political, and economic community. Greenhouse gases (GHGs), viz., carbon dioxide (76%), methane (16%), nitrous

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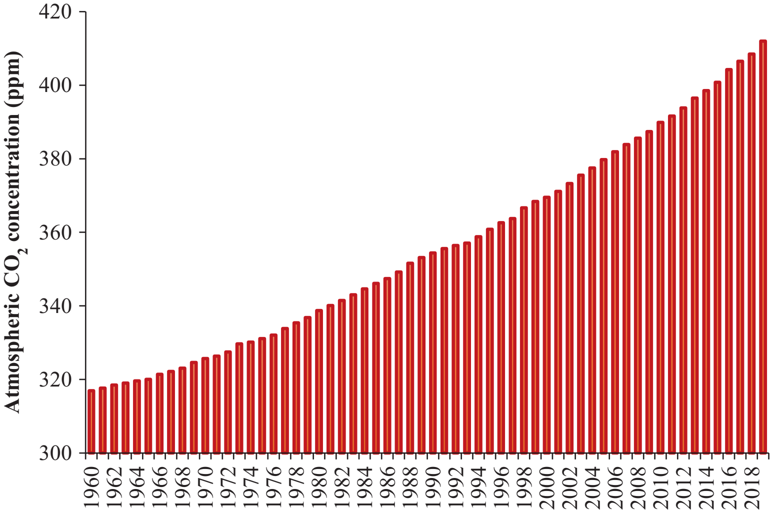


Fig. 11.1 Trends of CO_2 concentration in the atmosphere at Mauna Loa. (Source: NOAA 2019)

oxide (6%), and chlorofluorocarbons (2%), are likely to affect agricultural productivity and food security adversely through climate change (Ranjan and Yadav 2019; Malyan 2018; Fagodiya et al. 2017a; Kumar et al. 2016, 2017b; Pathak et al., 2016; Gupta et al. 2015, 2016; Kumar and Malyan 2016; IPCC 2014; Bhatia et al. 2013a, b). Malyan et al. (2016a, b) quoted that the rise in atmospheric greenhouses gases may result in rising of global mean temperature up to 1.5 °C by the end of the twenty-first century. Among all greenhouse gases, CO_2 only accounts for 76%, so it is considered most important. At the beginning of industrial revolution, atmospheric CO_2 concentration was 280 ppm (Rastogi et al. 2002), and it has now increased to 410 ppm in March 2019 (Fig. 11.1). The annual mean growth rate (differences in CO_2 concentration between the last month of the year [December] and the first month [January] of that year) was monitored by Global Monitoring Division of National Oceanic and Atmospheric Administration (NOAA) at Mauna Loa site. The rate of growth was 0.54 ppm/yr. in 1960 and it increased to 2.10 ppm/yr. in 1983 (Fig. 11.2). The growth rate of CO_2 in the atmosphere was 2.98 ppm/yr. in the year 2016, and it might rise over 3 ppm/ yr. in few upcoming years (NOOA 2019). The CO_2 growth rate is increasing continuously due to many anthropogenic actions, including fossil fuel combustion, deforestation, forest fire, automobile, etc.

Soil, plant, and ocean are the major natural sink for atmospheric CO_2. Recently, the scientific community enhanced the work on mitigating climate change and global warming by reducing atmospheric CO_2 concentration through carbon sequestration (Bhattacharyya et al. 2018; Mukherjee et al. 2018). Soil acts as both source (soil respiration) and sink (carbon sequestration) for CO_2, and soil respiration contributes to 20% of the total CO_2 emission to the atmosphere (Kumar et al. 2017a, b; Gupta et al. 2016; Rastogi et al. 2002). The global soils hold 3.3 times (2500 Gt C) as compared to carbon present in the atmosphere (Lal 2014). Out of 2500 Gt, soil

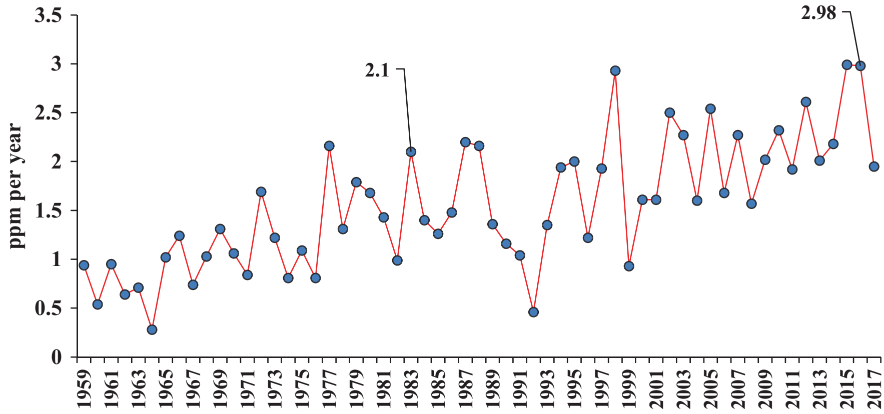


Fig. 11.2 Growth rate of carbon dioxide at Mauna Loa, Hawaii. (Source: NOAA 2019)

organic matter (SOC) and soil inorganic carbon retain 1550 Gt and 950 Gt, respectively (Lal 2014). The world soil pool of C is 4.5 times the size of C present in biomass (Lal 2014). In the soil carbon sequestration, biological soil crust plays a significant role. Soil fungi especially arbuscular mycorrhizal fungi enhance the soil carbon sequestration in different types of ecosystems. The objective of this study is to assess the carbon sequestration potential of fungi in soils and the factors affecting thereof.

11.2 Fungi and Carbon Sequestration

Carbon is the major building block in all living organisms. It exists in many forms such as soil organic matter, plant biomass, and CO_2 in the dissolved form in water and gas in the atmosphere. Carbon in soil is more than the total carbon in the atmosphere and plants biomass. Numerous small fungi in the soil, consist of hyphae that use carbon as a building block (Fig. 11.3). When this hypha dies, it is easily decomposed and its carbon is stored as soil organic matter for a long time (Treseder and Holden 2013). The process of long-term storage of carbon in the soil, terrestrial biomass, or the ocean so that the buildup of CO_2 in the atmosphere will be slowed down or reduced is known as carbon sequestration. In other words, carbon sequestration is defined as "*the capture and secure storage of carbon that would otherwise be emitted to or remains in the atmosphere*" (FAO 2000). In carbon sequestration, fungi play a significant role in the northern hemisphere of the Earth which help to combat global warming. In soil, fungi do symbioses association (mycorrhizal fungi) with plant roots and help the plants to utilize the nutrients from the soil. As a result, mycorrhizal fungi stimulate the plant's growth which results in the faster removal of atmospheric CO_2 through its conversion into plant biomass. There is a different pathway of converting the atmospheric CO_2 to plant biomass (Fellbaum et al. 2012).

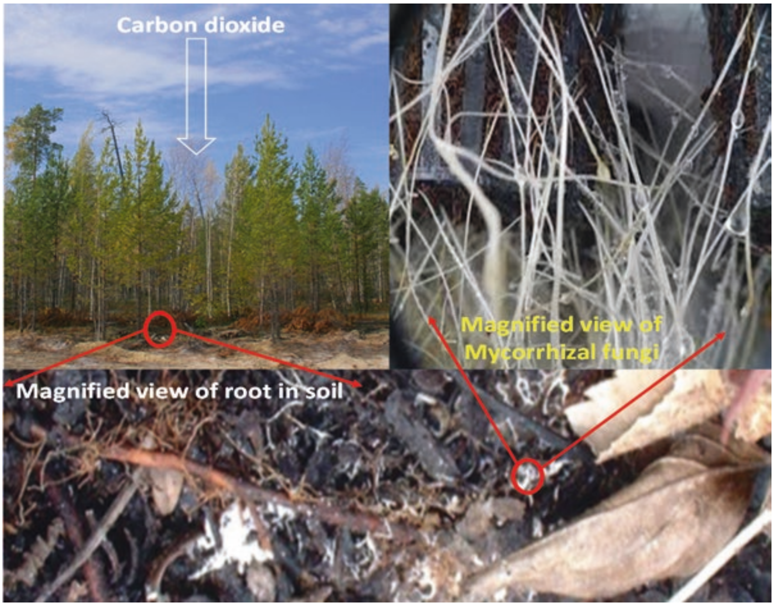
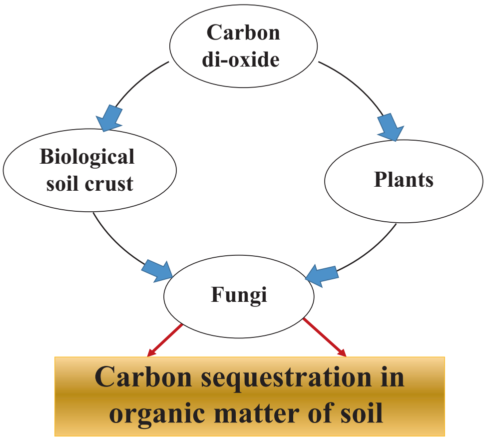


Fig. 11.3 Showing mycorrhizal fungi hyphae in soil

Fig. 11.4 Simplified method of carbon sequestration in soil organic matter by fungi



The photosynthates of the host plant are transferred to the intraradical hyphae followed by extraradical hyphae before it releases to the soil (Fig. 11.4). Carbon sequestration in soil depends on the volume and hyphal biomass of fungi (Solaiman 2014; Zhu and Miller 2003).

Fungus is a nonchlorophyllous organism and is heterotrophic (requires an organic source of carbon) in nature, i.e., it obtains its food from either dead organic matter (saprophytic) (Chaubey et al. 2019) or from the autotrophic/heterotrophic associates (parasitic and symbiotic). *Agaricus*, *Aspergillus*, *Morchella*, *Mucor*, *Penicillium*, *Rhizopu*s, *Saprolegnia*, etc. are the example of the saprophytic mode of nutrition. The parasitic fungi are *Peronospora*, *Puccinia*, *Fusarium*, *Pythium*, *Melampsora*, etc. The associate may be animal, plants, and microbes. If an associate is a plant, the autotrophic association can be stated as true symbiosis. The fungi can use a variety (e.g., yeast used the acetate) of the organic matter as a source of energy but the majority of them prefer carbohydrates. Glucose is a preferred carbohydrate for almost all the fungi as compared to fructose. Starch and cellulose are also used by some of the fungi which are capable of synthesizing hydrolytic enzymes. Organic acids are the least preferred sources of energy by most of the fungi. *Basidiomycetes* are able to utilize lignin as an energy source. Saprolegniaceae and *Blastocladiales* can grow only with organic nitrogen, i.e., amino acids. The organic matter is first dissolved by the extracellular enzymes, and then it is directly absorbed by diffusion either through the hyphal walls of the hyphae that penetrate the substratum or by the rhizoidal hyphae.

Lichens (a single composite thallus plant) are the best-explained association of fungi with the alga where the fungus provides the minerals, water from the substratum, and space for alga which in return supplies food. Mycorrhiza is the association of fungi with the roots of higher plants and can be ectomycorrhiza, endomycorrhiza, and ectoendomycorrhiza based on the positional association.

The input of the plant's organic matter into the soil carbon is both aboveground and belowground litter in the form of leaves, stem, flower, and roots. The plant also contributes some organic compounded inform of exudates to the soil. This contribution is known as rhizo-deposition. The rhizo-deposition is also an important carbon contribution of higher plants which is based on plant root architecture, environment, physiology, biochemistry, and chemical composition of the deposited matter. The litter's input is varying in quantity and depends on the climax community of the ecosystem. The belowground input mainly contributes to the organic matter and stabilizes their medium to long duration based on the physicochemical properties of soil and microbiota (Dignac et al. 2017; Clemmensen et al. 2015; Kuzyakov and Domanski 2000; Mendez-Millan et al. 2010).

Carbon sequestration entirely depends on the photosynthetic rate of the autotrophs and the respiratory losses of the autotrophs and symbionts (mycorrhizal fungi). These fungi utilize 5 to 20% of the net primary productivity of the symbiotic system (Luo and Zhou 2010). The change in the carbon assimilating or degradation rate can entirely change the carbon sequestration potential of the association until the change in both the processes is in the same direction and potential. The degradation of rhizo-deposited carbon is done by microorganisms. These microbes are present or associated with the specific plants and soils. The quantity of the rhizo-associate is also contributed majorly. The quantified contribution in the respiratory losses of these rhizo-associates especially mycorrhizal fungi is not reported in different associations separately. Thus, the exact carbon sequential potential of mycorrhizal fungi still remains to be estimated. However, few studies have confirmed in controlled and field experiments that carbon sequestration depends on plant photosynthesis and respiration through mycorrhizal fungi (Luo and Zhou 2010; Bahn et al. 2008;

Friedlingstein, et al. 2006; Ussiri et al. 2006). Global forest soils efflux into the atmosphere through belowground respiration has been estimated to be approximately 24 Pg C y^{-1} in which mycorrhizal fungi contribute about 16% (Zhang et al. 2007; Hu et al. 2005). Thus, increasing the sequestration potential of the mycorrhizal fungi can reduce the contribution drastically.

11.3 Factors Affecting Fungal Growth in Soil

Fungi have high plasticity and they easily adapt to adverse conditions in the soil. A diverse range of fungi is found in almost every type of ecosystem owing to the fact that fungi can adapt to a wide range of temperature and pH (Frac et al. 2018; Frac et al. 2015). Fungi activity in soil is affected by abiotic (physical disturbance, soil temperature, soil pH, soil texture, moisture, and salinity) and biotic (plant and other organisms interaction) factors, and it may influence the carbon sequestration activity of fungi (Kour et al. 2019; Rana et al. 2019; Yadav et al. 2017, 2018, 2019; Farc et al. 2018; Rouphael et al. 2015; Posada et al. 2008; Treseder and Allen 2000) (Table 11.1). Some factors affecting fungi activity in the soil are discussed below in brief.

11.3.1 Temperature

The Northern hemisphere consists of 67.3% of total Earth's landmass; Moritz et al. (2002) reported that global warming has led to a rise in temperature by ~1.5 °C. The IPCC (2007) predicted that by the end of 2100, the temperature may elevate to

Table 11.1 Factor affecting the fungi in soils

Factor	Remarks	References
Temperature	Soil warming results in rapid fungal respiration which results in carbon losses to the atmosphere	Hawkes et al. (2008)
	No effect on fungal carbon sequestration under soil warming	Rosenstock et al. (2018)
P-Fertilizer	On addition of N fertilizer fungal biomass increase which helps in carbon sequestration	Aliasgharzad et al. (2018)
	To an optimum level (20 mg kg^{-1}) shows a positive response while at a higher dose (40 mg kg^{-1}) shows a negative impact on fungal root growth	Aliasgharzad et al. (2018)
	Application of phosphorous fertilizer has a negative effect on fungal diversity in soil	Smith et al. (2011)
Pesticides	Have a direct and indirect negative impact on fungi diversity and carbon sequestration in soil	Willis et al. (2013)
Physical disturbances	Biocrust removal drastically affects inoculum potential of AM (Arbuscular Mycorrhiza) fungal mycelial due to web fragmentation	Jasper et al. (1989)

additional 4–7 °C which will affect all the ecosystem services. There are contradictory reports on the effect of soil temperature on the fungal diversity and activity (Rosenstock et al. 2018; Solley et al. 2017; Allison and Tresseder 2008; Fujimura et al. 2008; Zogg et al. 1997; Yadav et al. 2018). On one hand, some studies have reported significant changes in fungal activity; to the contrary, some others could not assess any change related to temperature. This suggests that the effect of temperature is species-specific. In Tundra, Fujimura et al. (2008) observed no change in fungal diversity even after soil warming. Warming of soil samples taken from the environment resulted in a significant change in fungal community of soil (Zogg et al. 1997). Rosenstock et al. (2018) observed that the soil warming from a range of 0–5.5 °C above the control has no or limited effect on the growth of ectomycorrhizal and no effect on community composition and fungal carbon sequestration in *Picea sitchensis* forest soils (Rosenstock et al. 2018).

11.3.2 Physical Disturbance

Disturbance in several ecosystems is a universal process and it affects all levels of biological organisms prevailing in that ecosystem. The causes of disturbance may be natural or anthropogenic. Anthropogenic physical disturbance in top soil (20–30 cm) results in fragmentation of fungal mycelia (Jasper et al. 1989) which results in a lower rate of soil carbon sequestration. Korb et al. (2003) reported that in the soil, fungi diversity recovered rapidly after a forest fire. On the other hand, in an agricultural field, tillage practices disturb the fungal diversity and they recover at a slow rate. However, in the Gangetic Plains of India, the fungal diversity was observed to recover at a rapid rate. The high rate of fungal recovery in Indian plains was due to a large diversity of spores (Oehl et al. 2005).

11.3.3 Soil pH

Soil pH is the primary factor affecting fungal activity in the soil and provides an environment that is essential for carbon sequestration in soil. Minor increases in pH are associated with higher root colonization by fungi in acidic soils with less phosphorus availability (Ge et al. 2017; Oehl et al. 2005).

11.3.4 Fertilizer

Phosphorus(P)-based fertilizers have environmental concerns related to eutrophication of fresh waterbodies. Generally, soil has an abundant amount of both inorganic and organic P in soil, but its bioavailability is very low for the crop and plants

(Sarabia et al. 2017). Mycorrhiza increased the P availability for host plant, and in return, fungi get the photosynthetic product and result in more development of hyphae which increases the soil carbon sequestration. Aliasgharzad et al. (2018) reported that application of 20 mg-P kg^{-1} soil showed positive fungal root growth while increasing the P dose to 40 mg kg^{-1}negatively affected the growth rate of fungi (Table 11.1).

11.3.5 Pesticide

Fungi in agricultural soils are exposed to different type of pesticides. Application of pesticide directly or indirectly affects the host plant and thus indirectly suppresses the rate of carbon sequestration by fungi in soils (Table 11.1). Zocco et al. (2011) reported that fungicides like fenpropimorph inhibit the growth and development of fungi in soil. Nevertheless, pesticides like dimethoate, fenamiphos, and aldicarb were not found to inhibit the fungal diversity (Karpouzas et al. 2014; Schweiger and Jakobsen 1998; Nemec 1985). Spokes et al. (1981) studied the impact of eight chemicals on the development of fungi. It was observed that aldicarb had negligible impact on fungi development, while fungicide chloroneb acted as development stimulator for fungal population in the soil. Then again, triadimefon and benomyl fungicides application had an inhibitory impact on fungal development (Spokes et al. 1981).

11.3.6 Moisture

Soil moisture is an important constituent for the growth of the soil fungi. The soil fungi and degradation of the rhizo-deposition material is highly influenced through the moisture percentage. The decrease in the moisture percentage can directly limit the availability of organic matter to the fungi, so that the rate of degradation can decrease and ultimately the growth of soil fungi can also get limited. Therefore, moisture also directly controls the soil temperature and soil heat flux. Moreover, the higher the soil temperatures, the lower is the soil moisture, especially in the topsoil horizon, and ultimately the lower will be the soil fungi due to the scarcity of the food material.

11.4 Research Gap and Future Recommendation

At certain places and in some of the ecosystems, fungi can play an important role in the sequestration of carbon dioxide present in the atmosphere by playing principal roles in fixation of organic matter in the soil and degradation. However, the mechanism of sequestration is not yet fully understood. There are certain avenues that need to be explored in order to have a deeper understanding of this phenomenon. Some of the gaps that have been observed from literature to direct the future research have been summarized as follows:

(i) The quantified contribution of soil and mycorrhizal fungi in different ecosystems and various associations has not yet been evaluated and reported. This quantification can serve a major role to define the direction of the soil and mycorrhizal fungi as a carbon sequestrate.
(ii) The minimizing of the respiratory losses of soil and mycorrhizal fungi can also enhance the carbon sequestration potential. Therefore, future research should be conducted in this direction.
(iii) The role and potential of different fungal communities along with different types of soil and mycorrhizal fungi can also serve to enhance the carbon sequestration in different ecosystems.
(iv) The factors influencing growth of fungi such as soil moisture, soil temperature, CO_2 enrichment, quality of rhizo-deposition, and precipitation changes control the heterotrophic respiration. Thus, the impact of these factors with respect to the soil and mycorrhizal fungi can also lend a hand to understand their behavior in changing the environment.
(v) Relevant studies in different interactions, i.e., moisture vs mycorrhizal diversity, soil temperature vs mycorrhizal composition and diversity, and soil temperature vs moisture, are very limited in respect of the soil fungal respiration and also poorly understood.
(vi) Contribution of mycorrhizal association on carbon storage in contaminated/mineral/nutrient-rich soil is not available.

Therefore, future research in this direction can help in improved understanding of the mechanism of fungal carbon sequestration.

11.5 Conclusions

Based on this study, the following conclusions can be drawn. The global soil carbon is more than the carbon present in the atmosphere, but the rising temperature due to global warming has the potential to affect the fungal diversity and fungal activity. The rate of soil carbon sequestration by fungi depend upon direct (quality and quantity of hyphae) and indirect (soil pH, texture, moisture, soil management, physical disturbance, pesticide application, etc.) factors of the ecosystem. There are three important strategies to combat climate change: development of less or zero carbon fuel, limiting of fossil energy use, and carbon dioxide sequestration from atmosphere or emission point source through abiotic (engineered) or biotic methods (photosynthesis). Soil carbon sequestration by fungi in soil is the environmentally sound method to reduce the carbon dioxide levels in the atmosphere.

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