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The Crucial Role of elevated Carbon dioxide and Temperature on Soil Biodiversity in Agricultural Ecosystem: A Comprehensive Review

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ABSTRACT: Soil biodiversity encompasses a rich array of organisms present in the soil and have profound implications for ecosystem functioning and long-term sustainability of agro ecosystem. Rise in atmospheric carbon dioxide (CO_2) concentration and temperature are two major drivers of global climate change scenario. This review article delves into the impact of elevated carbon dioxide (E[CO_2]) and temperature on crop growth and yield and its effect on soil biodiversity. It elucidates the current understanding of how CO_2 and temperature changes affect crop yield and soil biodiversity. Increased CO_2 concentrations can stimulate or dampen plant growth with marked influence on crop yield and global food security. The E[CO_2] affects the functional and structural composition of soil microbial community through its effects on plant C inputs to soil, soil moisture, or nutrient availabilities. Temperature influences the physiology, activity, and survival of both crops and soil organisms. Warmer temperatures disrupt the crop's optimal temperature with adverse effect of crop physiological processes. Shifts in temperature regimes may also affect the distribution and abundance of different soil organisms, potentially favoring some species while suppressing others. Enhanced temperature also accelerates decomposition rates, nutrient cycling processes, altering organic matter dynamics and nutrient availability in the soil. The combined effects of elevated CO_2 and temperature on soil biodiversity are complex and context-dependent. The interplay between elevated CO_2, temperature, and soil biodiversity in agricultural ecosystems are complex and multifaceted which requires further investigation. To mitigate these adverse effects, strategies such as conservation agriculture practices, sustainable farming methods, and precision nutrient management are required to promote soil biodiversity enhance resilience, and productivity under changing environments. Continued effort is essential to unravel the mechanisms involved in these interactions.

Keywords: Climate change; GHG emissions; Global warming; soil microbial communities; plant growth and yield.

INTRODUCTION

Soil biodiversity is defined as the variability of living organisms in soil and the ecological complexes of which they are part; this includes diversity within species (genetic diversity), between species, and of entire ecosystems (UNEP, 1992). It constitutes a rich array of organisms residing in the soil, whether they are single-cell organisms or multi-cell animals or plants. The soil biota includes diverse groups of microorganisms like fungi, bacteria, algae and virus as well as the micro fauna such as protozoa and nematodes. These soil organisms play vital roles in nutrient cycling, regulating the dynamics of soil organic matter, carbon sequestration and green house gas (GHG) emission, modifying soil physical structure and water regimes, enhancing nutrient acquisition and plant health (Chen *et al*., 2019). Soil biodiversity is more extensive than in any other environment on the globe.

In the current global climate change scenario, continuous rise in atmospheric carbon dioxide (CO_2) concentration and temperature could disturb the dynamics of soil biodiversity and associated services (Malhi *et al*., 2020). Since preindustrial times, CO_2 concentration in the atmosphere has increased from 280 ppm to 410 ppm at present with a temperature rise of 0.18° C per decade (IPCC, 2021). The increase in atmospheric CO_2 concentration is largely attributed fossil fuel combustion, land use change and agriculture. Agriculture emission of CO_2 includes emissions from respiration of soil organisms and plant roots. This further cause global temperature to rise leading to depletion of soil organic matter enhancing the microbial decomposition and release CO_2.

To confront these challenges and harness the potential benefits, it is crucial to advance our understanding of how elevated CO_2 and temperature impact soil biodiversity in agricultural ecosystems. This knowledge will enable the development of targeted management practices that mitigate the negative effects and promote the conservation and enhancement of soil biodiversity. Such practices may include conservation agriculture techniques, sustainable farming approaches, and precision nutrient management. In this review, a brief overview of the impact of elevated CO_2 and temperature on soil biodiversity in agricultural ecosystems is provided. The direct and indirect effects of these environmental factors on crop yield, soil microbial communities, macrofauna and nutrient cycling processes has been explored. Additionally, potential management strategies that can be employed to maintain soil biodiversity and ensure sustainable agricultural practices in the face of changing CO_2 levels and temperature regimes is discussed.

TRENDS OF CO_2 IN AGRICULTURAL ECOSYSTEM

Agroecosystem is one of the main sources of CO_2 emission to the atmosphere. According to IPCC (2007), the CO_2 concentration in the atmosphere can range from 500 to 1000 ppm by the end of 21st century depending on future emission rate of GHGs and global surface temperature is projected to increase by as much as 1.8 - 4°C. The current annual average concentration of CO_2 is 410 ppm and the concentration has been increasing since 2011 (IPCC, 2021). In India, water scarcity and GHGs emission are two key environmental issues for crop production. Indian agriculture contributes about 16% of India's total GHG emissions, emitting 417.22 million tons of CO_2 equivalent each year, of which 74% is CH_4 and 26% is N_2) (MoEFCC 2018). Thus, the total agricultural GHGs emissions in terms of carbon equivalent has increased by 161% during last 50 years mainly due to adoption of input and energy intensive agricultural practices like application of N fertilizer, use of farm machineries etc. (Diksha and Devakumar, 2018). Among the different agricultural crops in India, the estimated total carbon footprints of major foodgrains such as rice, wheat and maize were 2.44, 1.27 and 0.80 t CO_2 e ha^{-1} respectively (Nayak *et al*., 2022).

A. Effect of elevated CO_2 on crop growth and yield

Many researchers reported that elevated CO_2 (E [CO_2]) has a strong influence on the growth, development, seed yield and biochemical metabolism of plants. The trend in term of crop responses to E [CO_2] is expected to have a marked influence on the global food supply and may threaten the nutrition of human beings (Myers *et al*., 2014). The effects of E [CO_2] vary among different types of plant. The E[CO_2] stimulates photosynthesis, enhances C deposition in soil, and changes the rhizosphere conditions of plants, leading to increase in biomass and yield of crops (Niu *et al*., 2016; Xu *et al*., 2016). The E[CO_2] directly enhances the photosynthesis of C3 plants but not of C4 plants (Wang *et al*., 2012). In some C3 plant species, the enhancing effects of E[CO_2] on photosynthesis occur only after short-term treatment and decrease or even disappear after long- term treatment, a phenomenon called "CO_2 acclimation" (Bloom *et al*., 2002). Moreover, E[CO_2] inhibits NO_3^- assimilation and decrease organic N content of plants, resulting photosynthesis declines, which could be an important factor in "CO_2 acclimation" (Bloom *et al*., 2010).

Up to the level of 700 ppm E[CO_2] does not affect yield of *Brasica napus* L. and also increased the biomass yield while the combined effect of elevated CO_2, temperature (+ 5°C) and O_3 (+ 40ppb) decreased yield and plant biomass (Frenck *et al*., 2011). The effect of E[CO_2] (780 ppm) in horticultural crops like guava (*Psidium guajava* cv. Pedro Sato) favors seedling growth and increase starch and tannin accumulation in plants resulting anti –herbivore substance in latter stage (Mendes de Rezende *et al*., 2014). The response of crops to E[CO_2] also differs due to endosperm morphology as can be seen from wild rice and domesticated rice response to E[CO_2] (Rahman *et al*., 2021). E[CO_2] increased the rice yield and may lead to N limitation and potentially influence the sustainability of agricultural production (Wu *et al*., 2020; Rahman *et al*., 2021). The effects of E [CO_2] on different crops under different growing environment are given in Table 1.

B. Effect of elevated CO_2 to soil microbial diversity

The E[CO_2] affect functional and structural composition of soil microbial community though its effect on plant C inputs to soil, soil moisture, or nutrient availabilities (Rajkumar *et al*., 2013; William *et al*., 2000). A long-term (14 years) effect of E[CO_2] (275 ppm higher than ambient) on soil microbial communities using *16S rRNA* gene amplicons and a GeoChip microarray showed modification of both taxonomic and functional gene compositions of the soil microbial community under grassland conditions (Yang *et al*., 2019).The E[CO_2] (560 ppm) also shift affected the bacterial community composition in the rhizosphere of Korean red pine (*Pinus densiflora*) resulting in abundance of three bacterial phyla, *Proteobacteria*, *Acidobacteria*, and *Actinobacteria* (Lee *et al*., 2021). A meta-analysis of965 observations from 122 studies showed that E[CO_2] shifts soil microbial communities from K- to r-strategists (Sun *et al*., 2021).A FACE experiment in China indicated that E[CO_2] levels were found to increase the population of omnivores-predators, as well as enhance the values of maturity index and structural index within the nematode community during the jointing stage of wheat (Li *et al*., 2007). Further, Luo *et al*. (2021) reported that rising CO_2 levels promoted the resilience of nano particles ($nCeO_2$ and nCr_2O_3) - resistant bacterial populations, particularly members of Alpha proteobacteria, Gamma proteobacteria and Bacteroidia, which are known for their carbon use capability. The study also suggested that E[CO_2] levels promoted the growth of oligotrophic bacteria like *Acidobacteriaceae* and *Bryobacteraceae*over copiotrophic bacteria like *Sphingomonadaceae*, *Caulobacteraceae*, and *Bacteroidaceae* (Luo *et al*., 2021).

Table 1: Effect of elevated CO$_2$ and temperature under different crops.

Crop	CO$_2$ level	Temperature	Yield / other effects	Growing environment	References
Rice	700 ppm	—	Increased seed length , weight and 1000 seed weight and decreased total N content	Glasshouse	Rahman *et al.* (2021)
Wheat	550 µmol mol^{-1} with high irrigation	—	Increased seasonal wheat biomass (10%) and decreased seasonal evapotranspiration (5%)	FACE exp.	Grant *et al.* (1999)
Wheat	A: 400 µmol L^{-1} E: 800 µmol L^{-1}	—	E [CO$_2$] increased grain no. and starch concentration while decreased grain protein concentration.	Greenhouse cells	Jiang *et al.* (2021)
Wheat, Rice, Maize, Soybean	—	Each ºC increase in global mean temperature	Estimated yield reduction up to 6% wheat, 3.2% Rice, 7.4% Maize and 3.1% Soybean	Modeling methods (global gird based and local point based), statistical regression and field warming experiments.	Zhao *et al.* (2017)
Brasica napus L.	700ppm	—	Increased yield	Phytotron environment	Frenck *et al.* (2011)
	—	+ 5° C	Decreased yield by 38 to 58%		
	700 ppm CO$_2$ + 40 ppb O$_3$	+ 5° C	Decreased yield		
Soybean	800 µmol mol^{-1}	—	Increased plant growth including photosynthesis but reduced mineral elements in the leaves	Growth chamber	Zheng *et al.* (2020)
Tomato	E1: 700 ppm	+ 2º C	Advanced in different phenophases like initiation of branch, flower, fruit and fruit maturation, and reduced the crop cycle	Open Top Chambers (OTC)	Rangaswamy *et al.* (2021)

Table 2: Effect of elevated CO$_2$ and temperature on microbial diversity.

Crop	CO$_2$	Temperature	Growing environment	Microbial diversity	References
Wheat	A: 400 µmol L^{-1} E: 800 µmol L^{-1}	—	Greenhouse cells	Reduced the Grain, root and leaf endophytic microbiota diversity in E [CO$_2$] and also reduced bacterial community but fungal community remain same in A and E [CO$_2$]	Jiang *et al.* (2021)
Rice	A: 400 ± 10 µmol mol^{-1} E: 550 ± 20 µmol mol^{-1} E: 700 ± 20 µmol mol^{-1}	—	Open top chamber (OTC) design	Increased denitrifier and decreased nitrifier population under elevated CO$_2$ environment	Kumar *et al.* (2021)
Rice	+ 60-100 µmol mol^{-1}	+ 2ºC	OTC system	Increased the abundance of ammonia oxidizing bacteria and nitrification rate	Waqas *et al.* (2021)
Wheat	A: 370 µmol CO$_2$ mol^{-1} E: 570 µmol CO$_2$ mol^{-1}	—	FACE system	E [CO$_2$] increased the total number of nematode as compare to the ambient CO$_2$.	Li *et al.* (2007)
Rice	A: 392–430 µmol mol^{-1} E: 500 µmol CO$_2$ mol^{-1}	+ 1.5 to 2ºC	FACE system	E[CO$_2$] and raising temperature exhibited an additive influence on CH$_4$ fluxes and methanogen abundances	Wang *et al.* (2018)
Aspen (Populus tremuloides)	CO$_2$: Ambient and E, 560 µmol mol^{-1} O$_3$: Ambient and E, 50-60 nmol mol^{-1}	—	FACE system	Exhibited minor changes in fungal and bacterial communities at a depth of 0-5 cm under long term experiment (9 years)	Dunbar *et al.* (2014)

Rice	A: 400 ± 10 μmol mol^{-1} E: (550 ± 20 μmol mol^{-1}	—	OTC system	Long term exposure of E[CO_2] decreased the OTUs of Glomarales and increased the OTUs of Diversisporale	Panneerselvam *et al.* (2019)
Wheat	A: 380 μmol mol^{1} E: 550 μmol mol^{-1}	—	FACE system	E [CO_2] and N fertilization significantly affected the collembolans abundance and diversity	Sticht *et al.* (2006)
—	—	+2ºC	OTC system	For both alpine and subalpine soils, bacterial abundance surpassed fungal abundance	D'Alo *et al.* (2021)

E [CO_2] also increase the abundance of bacteria and ammonia-oxidising bacteria and decrease fungal community under Cd exposure by increasing pH, total carbon, water soluble-organic carbon, and C/N ratio and decreasing the total and soluble Cd content in rhizosphere soils. E [CO_2] increased the abundance of *Acidobacteria, Chloroflexi, Ascomycota,* and *Thaumarchaeota* phyla, while reducing the abundance of *Proteobacteria* and *Actinobacteria* phyla in Cd-exposed rhizosphere soils. The dominant taxa also exhibited significant shifts in abundance (Jia *et al.* 2020). The effects of E [CO_2] on microbial diversity under different growing environment are given in Table 2.

IMPACT OF RISING GLOBAL TEMPERATURE ON AGRICULTURAL ECOSYSTEM

Rising global temperatures have significant consequences on multiple facets of the agroecosystem, exerting a profound impact on agricultural productivity and sustainability. According to IPCC (2021), successive warming has been observed in each of the past four decades compared to the preceeding decades since 1850. The global surface temperature during the first two decades of the 21st century (2001-2020) was approximately 0.99 (0.84-1.1) ºC higher than the temperature recorded between 1850 and 1900. From 2011 to 2020, the global surface temperature increased by about 1.09 (0.95 to 1.2) ºC compared to the period of 1850-1900, with land experiencing a larger increase (around 1.59 [1.34 to 1.83] ºC) compared to the ocean (approximately 0.88 [0.68 to 1.01] ºC). The increase in global surface temperature since IPCC Assessment Report 5 is mainly attributed to additional warming observed after 2003-2012 (+ 0.19 [0.16 to 0.22] ºC). The major effect on crop and microbial diversity is discussed as follows.

A. Effect of rising temperature on crop growth and yield

Every crop has its own optimal temperature and is highly sensitive to temperature fluctuations. Elevated temperatures disrupt the optimal temperature range that different crops require for growth, resulting in reduced productivity. Crop phenology is also susceptible to rising temperatures. As temperatures increase, the phenological stages of plants may shift, disrupting the synchronization with pollinators and disturbing ecological interactions (Visser and Both 2005). A shorter duration of the growing cycle and an extended vegetating season are some of the damages related to extreme temperatures (Funes *et al.*, 2021). In addition, rising temperatures induce shifts in crop suitability and distribution patterns. Crops that have traditionally been grown in a particular region may become less viable due to changing climate conditions (Datta *et al.*, 2022). This showed that certain heat-tolerant crop varieties may expand their range. When temperature increases beyond 35ºC disrupt rubisco, the central enzyme of photosynthesis, causing a halt in the photosynthetic process (Griffin *et al.*, 2004). Heat stress negatively affects antioxidants enzymes and floret development that can lead to sterility in cereals (Saini and Aspinal 1982; Gong *et al.*, 1997). Temperature extremes in multiple countries can lead to potential wheat yield reductions by 6% per ºC increase in temperature (Asseng *et al.*, 2015). In contrast to the above reports, Wang *et al.* (2021) observed that increase in temperature boosts corn and soybean yield by 12% and 8%, respectively, and is attributed to a reduction in temperature stress caused by delayed planting under the changing climate change scenario in Canada. Zhao *et al.* (2017) reported that with each ºC increase in global mean temperature, the estimated yield reduction is 6% in wheat, 3.2% in rice, 7.4% in maize and 3.1% in soybean. Frenck *et al.* (2011) reported that an increase of 5 ºC in temperature led to a decrease in *Brassica napus* L. yield by 38 to 58%. Furthermore, increasing temperatures exacerbate water scarcity issues such as drought, posing a significant challenge to agriculture (Wang and Huang, 2004). With higher temperatures, evaporation rates escalate, leading to decreased soil moisture levels and limited water resources. This situation intensifies drought conditions; further restricting crop water availability and compounding the difficulties faced by farmers (Mallareddy *et al.*, 2023). Water deficit during the meiotic phase results in significant reduction, ranging from 35% to 75%, in grain set of wheat and rice (Saini and Aspinall 1981; Sheoran and Saini 1996). Drought stress in rice disrupts the processes of fertilization and anthesis, leading to decreased harvest index and grain set by 60% (Garrity and O'Toole 1994). Another bearing of related elevated temperature is its effect on pests and diseases in agricultural ecosystems which could impact crop yield. Warmer temperatures create unpredictable conditions for certain pests and pathogens to become invasive causing higher infestation rates and disease incidence among crops (Skendzic *et al.*, 2021; Schneider *et al.*, 2022). This results in direct crop damage, necessitating additional pest control measures and adding to production costs and environmental concerns. The effects of temperature on plant growth and yield under different growing environment are given in Table 1.

B. Effect of rising temperature on soil microbial diversity

Rising temperature has profound influence on the composition and dynamics of microbial communities. As temperatures increase, shifts in species composition occur with certain microbial populations becoming more dominant while others decline (Silva *et al.*, 2022). This leads to alterations in overall microbial diversity within ecosystems. The heat-tolerant species tend to thrive under higher temperatures, potentially outcompeting and suppressing other microbial populations, resulting in a decrease in diversity (Donhauser *et al.*, 2020). In a 26-year warming experiment, Melillo *et al.* (2017) found reduction in soil microbial biomass and changes in community composition. Rising temperatures may also contribute to the proliferations of pathogenic microbes, especially those capable of multiplying in warmer water environments, as observed with *Candida auris*, a multi resistant yeast of significant nosocomial impact (Casadevall *et al.* 2019; Arora *et al.*, 2021). Parasitic protozoa like *Acanthamoeba* and *Naegleria fowleri* may also benefit from higher temperatures (WHO, 2021).

Rising temperature can also impact the metabolic activity of microbes, affecting nutrient cycling and ecosystem processes. Some microbial species may exhibit increased metabolic rates in response to higher temperatures, while others may become less active or under functional changes. Also, the symbiotic relationships between microbes, plants and animals can be disrupted by temperature changes, potentially leading to imbalances within ecosystems. This disruption can have severe consequences on health and functioning of host organisms. Ultimately, the alterations in microbial diversity caused by rising temperatures can impact ecosystem resilience and its ability to withstand environmental disturbances. The rise in temperature leads to an increase in microbial maintenance demand, causing an elevation in microbial activity in the soil and subsequent soil respiration (Rustad *et al.*, 2001; Wu *et al.*, 2011). Changes in soil respiration are influenced by various factors such as alterations in microbial community structure (Balser *et al.*, 2006), availability of substrates (Davidson and Janssens, 2006), quality and quantity of plant litter (Rustad *et al.*, 2001) and the abundance of accessible carbon (Fierer *et al.*, 2005) due to increased temperatures. The sensitivity of microbial metabolism and their activities to temperature causes a direct impact on the rates of soil microbial respiration (Classen *et al.*, 2015a,b). However, significant changes in microbial community composition and adaptations leading to increased soil respiration are unlikely to occur unless other factors such as limited substrate availability, moisture, or alterations in forest stand composition/ structure are present (Schindlbacher *et al.*, 2011). Soil respiration shows a positive correlation with temperature but may be suppressed under low or high moisture conditions (Luo and Zhou 2006). Additionally, changes in precipitation patterns can affect soil temperature and moisture fluctuations, further influencing soil respirations Nottingham *et al.* (2022) reported marked decline in microbial diversity, especially of bacteria, with 3 to 8 ºC warming demonstrating a break down in the positive temperature- diversity relationship observed elsewhere. Also, the microbial community composition shifted with warming, with many taxa no longer detected and other enriched, including thermophilic taxa. This transition within the community led to an adaptation to higher temperatures, allowing us to forecast alterations in soil CO_2 emissions. Understanding these effects is crucial for effectively mitigate the impacts of climate change on microbial communities. The effects of temperature on different microbial diversity under different growing environment are given in Table 2.

EFFECT OF CONCURRENT ELEVATED CO_2 AND TEMPERATURE ON CROPS AND SOIL BIODIVERSITY

Concurrent elevated CO_2 and temperature is likely to have significant impacts on crop growth and soil biodiversity directly through its effect on physiology, temperature sensitivity and growth rates although results are inconsistent and complex. Combine E[CO_2] and elevated temperature increased growth and development of potato (Lee *et al.*, 2020) and tomato (Rangaswamy *et al.*, 2021), and increased of potato yield by 20.3% (Lee *et al.*, 2020) and soybean yield by 65% (Lenka *et al.*, 2017). Zhang *et al.* (2017) reported that there was a positive response on combined effect of E[CO_2] and elevated temperature on dry matter yield and C/N ratio of cotton leaves at different growth stages.The advanced phenology of weedy species in *Chenopodium album* (C3) and *Setaria viridis* (C4) was found in elevated temperature while the combine effect of E[CO_2] and elevated temperature increased the biomass and seed weights of *C. album* by 33.9 and 114.4%, respectively as compare to control (Lee, 2011). Across multiple models, Wang *et al.* (2021) reported that the average impacts of climate change showed a 16 and 14% increase in corn and soybean yield in Canada.

Increased CO_2 concentrations can enhance the growth and activity of certain soil microorganisms, such as bacteria and fungi. This can lead to changes in microbial community composition and diversity. Some studies have shown that elevated CO_2 levels can favor certain microbial species over others, altering the overall microbial diversity in the soil. The combination of E[CO_2] and raising temperature resulted in additive effects on CH_4 fluxes and methanogen abundances, with a correlation between CH_4 fluxes and CH_4 abundances. Seasonal CH_4 emissions were increased by 28-120% with E[CO_2], 38-74% with rising temperature, and 82-143% with the combined effect. Neither E[CO_2] nor rising temperature impacted the diversity of methanogenic community and the dominant methanogenic genera viz. *Methanosaeta*, *Mathanosarcina*, *Methanobacterium*, *Methanocella*, and *Methanoregula* in rhizosphere soil. However, E[CO_2] shift the relative abundances of acetoclastic to hydrogenotrophic methanogens and rising temperature stimulated CH_4 emissions by increasing CH_4 production per predominant methanogen genus. In addition to this, the combine effect of E[CO_2] and canopy warming on CH_4 emissions was also attributed to changes in the composition of methanogenic archaea induced by E[CO_2] and increased activity of methanogenic archaea stimulated by warming in rice paddies (Wang *et al.*, 2018). The prolonged exposure of paddy soil (8 years) to E[CO_2] (550 ppm) significantly diminished the prevalance of commonly found arbuscular mycorrhiza like *Claroideoglomus* and *Glomus* genera, in a sub-humid tropical environment (Panneerselvam *et al.*, 2019). Sauze *et al.* (2017) illustrated that the fluxes of soil-atmosphere CO_2, carbonyl sulphide, and $CO^{18}O$ are significantly influenced by variations in soil pH and light availability through the modulation of microbial community structure. This supports the notion that various members within the microbial community exhibit distinct classes of carbonic anhydrase, each with varying affinities towards CO_2 and carbonyl sulphide. Further, a long term experiment (14 years) in California annual grassland found that both the taxonomic and functional gene compositions of the microbial communities were altered by E[CO_2]. Taxa with higher ribosomal RNA operon copy numbers, which respond positively to resource availability, decreased under E[CO_2], while taxa with lower copy numbers increased. Additionally, key genes involved in nitrogen fixation and ammonia oxidation showed significant decreases, along with a decline nitrifying enzyme activity. E[CO_2] also affected microbial genes associated with carbon degradation, while those related to carbon fixation remained largely unchanged (Yang *et al.*, 2019).

EFFECT OF ELEVATED CO_2 AND TEMPERATURE ON NUTRIENT CYCLING AND SOIL FAUNA

Soil biodiversity is closely linked to nutrient cycling processes. Elevated CO_2 concentrations can influence the rates of nutrient cycling by affecting the activity and composition of soil microbial communities. For example, increased CO_2 can stimulate the decomposition of organic matter and enhance nutrient mineralization. However, the responses can be complex and depend on various factors such as soil type, plant species, and nutrient availability. Temperature changes can further influence nutrient cycling rates by affecting enzymatic activity and microbial processes. According to Kumar *et al.* (2021), the activities of enzyme like β-glucosidase, urease, and fluorescein diacetate were enhanced by E[CO_2] levels, leading to notable impacts on soil N dynamics. Using the path modeling, it was observed that the population of nitrifiers and denitrifiers had a direct influence on N_2O emission, with the effect being more pronounced under E[CO_2] compared to ambient CO_2 levels. The predictive models developed for N_2O emission provide clear evidence that the influence of different CO_2 levels is more prominent during the rice vegetative stage rather than the reproductive stage. Another long-term field experiment for 9 years also showed that E[CO_2] increased the SOC content, microbial biomass N and carbon and thereby increasing the abundance of ammonia-oxidising bacteria (AOB) up to 181% and soil nitrification rate (96%). Elevated temperature also led to an increase in soil nitrification rate (58%). Further the combine effect on E[CO_2] and rising temperature also enhances the AOB gene abundance and soil nitrification rate. Changes in temperature can accelerate the decomposition of organic matter, potentially altering soil carbon storage and nutrient availability. Consequently, climate change is expected to increase the population size of AOB without significant community restructuring and promote nitrification in paddy soils, leading to enhanced nitrogen availability with implications for crop productivity, N_2O emissions, and nitrate leaching. (Waqas *et al.*, 2021). E[CO_2] levels can affect the quantity and quality of plant inputs into the soil, which can in turn influence soil organic matter dynamics (Kuzyakov *et al.* 2018; Carillo *et al.*, 2010). E[CO_2] can affect the quality of plant litter that enters the soil. Under higher CO_2 concentrations, plant may produce more labile carbon compounds and less lignin, resulting in litter that decomposes more rapidly (Cha *et al.*, 2017). The acceleration of litter decomposition was observed with a 3 ºC temperature increase, suggesting that future warming will have a direct impact on C and N cycling (Salah and Scholes 2011). The E[CO_2] increased the soil N mineralization capacity up to 16.2 % as compare to ambient CO_2 and the effect is influenced by fertilization and rice cultivar (Wu *et al.* 2020). Changes in temperature also affect evaporation rates and soil water content (Samarakoon and Gifford 1995). E[CO_2] not only increased the water use efficiency but also improve drainage, leading deeper soil moister retention (Nelson *et al.*, 2004). This altered soil moisture conditions can impact the distribution and activity of soil organisms, including soil microorganisms and soil fauna, indirectly influencing soil biodiversity.

Soil fauna such as earthworms, nematodes, mites, and insects also play crucial roles in nutrient cycling and are significantly influenced by elevated temperature and E[CO_2] and. The response of soil fauna to elevated temperature can vary depending on the species, but generally, higher temperatures can increase metabolic rates and alter the life cycle and behavior of soil organisms. Research indicates that a mere 2ºC temperature rise may lead to insects undergoing an additional one to five life cycles per season (Yamamura and Kiritani 1998). Insects that spend a significant portion of their life cycles in soil may experience temperature changes more gradually compared to those living above ground. This is because the soil has insulating properties that effectively buffer temperature shifts (Bale *et al.*, 2002). The warmer winter temperatures, which can result in reduced winter mortality among insects, may have a significant impact on increasing insect populations (Harrington *et al.*, 2001). It is important to note that insect species diversity tends to decrease at higher latitudes and altitudes (Andrew and Hughes 2005) suggesting that rising temperatures could lead to an increase in the number of insect species attacking various hosts in temperature climate (Bale *et al.*, 2002).

STRATEGIES TO MAINTAIN SOIL BIODIVERSITYUNDER CHANGING CLIMATE SCENARIO

Conserving the natural soil biodiversity is vital for maintaining and functioning ecosystem services, such as nutrient cycling, carbon sequestration, vegetation health, plant growth as well as soil stability (Delgado-Baquerizo *et al*., 2020; Shi *et al*., 2021; Wang *et al*., 2023). One potential management method for soil biodiversity in agricultural ecosystems under E[CO_2] and elevated temperature conditions is the implementation of conservation agriculture practices (Carceles Rodriguez *et al*., 2022). Conservation agriculture with minimal soil disturbance, permanent soil cover, and inclusion of short duration legume can help to preserve and enhance soil biodiversity by reducing the negative impacts of E[CO_2] and temperature on soil organisms. Adoption of sustainable farming practices such as crop rotation, cover cropping, and organic farming methods can maintain soil biodiversity. These practices promote the growth of diverse plant species, enhance organic matter content in the soil, and foster beneficial microbial activity, thus supporting soil biodiversity. Implementing effective soil nutrient management strategies, such as precision fertilization and balanced nutrient application, can help maintain soil fertility and support diverse microbial communities. These strategies ensure that essential nutrients are supplied to plants while minimizing nutrient imbalances that can negatively impact soil biodiversity. Integrating trees within agricultural landscapes can provide additional benefits for soil biodiversity and mitigate climate change (Albrecht and Kandji 2003). Introduction of horticultural cash-crops, coupled with the abandonment of subsistence cereals, leads to changes in farmers' nutritional inputs, affecting both calorie intake and nutrient availability. Furthermore, farmers' knowledge plays a vital role in comprehending patterns in crop diversity and can aid in devising strategies to adapt to the challenges posed by climate change.

CONCLUSIONS

The influence of CO_2 and temperature on soil biodiversity in agricultural ecosystems is a critical concern given the ongoing challenges of climate change scenario. It is evident that these environmental changes disrupt the delicate balance of the soil ecosystem, leading to alterations in species composition, functional diversity, and nutrient cycling processes. This investigation, highlights that elevated CO_2 levels tend to favor specific microbial groups, leading to shifts in community dynamics and potentially affecting nutrient availability in the soil. Additionally, increasing temperatures can exert both direct and indirect impacts on soil organisms, influencing their activity, reproduction and survival rates. The combined effects of these factors can exacerbate the vulnerability of agricultural ecosystems to environmental stresses and, consequently, impact crop productivity and overall agricultural sustainability. It is imperative to continue exploring the intricate relationships between CO_2, temperature, and soil biodiversity in agricultural ecosystems.

FUTURE SCOPE

To enhance our understanding of this complex interaction and pave the way for more effective mitigation and adaptation strategies, the following aspects should be emphasized:

1. **Long term studies**: Conducting extended experiments that stimulate real-world conditions will allow researchers to observe how soil biodiversity responds to changing CO_2 concentrations and temperature trends over time. Long-term data will offer valuable insights into the resilience and adaptability of soil organisms to prolonged climate perturbations.
2. **Multi-dimensional approaches**: Incorporating diverse analytical techniques such as metagenomics, stable isotope analysis, and advanced modeling can provide a comprehensive view of soil biodiversity and its functional implications. A multidisciplinary approach will help identify hidden interactions and intricate responses within the soil ecosystem.
3. **Restoration and management strategies**: research should focus on developing sustainable agricultural practices that mitigate the negative impacts of elevated CO_2 and temperature on soil biodiversity. Implementing practices like cover cropping, reduce tillage, and organic farming can enhance soil health and foster biodiversity conservation.
4. **Climate change mitigation efforts**: Addressing the root cause of the problem, i.e., reducing CO_2 emissions, remain vital. Supporting and promoting policies that encourages the adoption of renewable energy sources and sustainable land use practices will contribute to stabilizing CO_2 levels and minimizing temperature increases.
5. **Climate-smart agriculture:** Integrating climate-smart agricultural practices, which prioritize climate adaptation and resilience, can aid in sustaining soil biodiversity while ensuring food security for a growing global population.
6. **Education and awareness**: Public awareness campaigns and educational programs can foster a deeper understanding of the significance of soil biodiversity in agricultural ecosystems. Encouraging farmers, policymakers, and the general public to value and protect soil life is crucial for fostering a sustainable and resilient future.

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