Unveiling How Climate Warming Alters Soil Organic Carbon Transformation: Insights from Microorganisms

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Abstract

Global climatic shifts significantly affect the functionality of terrestrial ecosystems, with soil organic carbon (SOC) being vital for sustaining their productivity and long-term viability. The excessive release of greenhouse gases, predominantly CO_2, has triggered ongoing global warming. Microorganisms act as the driving force behind SOC turnover and serve as critical intermediaries through which warming influences SOC storage and chemical traits. While climate warming has led to a reduction in organic carbon stores in most farmlands and forests, grasslands have seen an increase in organic carbon levels. This discrepancy is likely tied to the balance between microorganisms' breakdown of organic carbon for energy and their conversion of it into stable forms.

Rising temperatures, coupled with higher atmospheric CO_2, boost plant growth and photosynthesis, thereby increasing the input of organic carbon into soils. These external carbon sources are transformed by microorganisms into stable reserves, which in turn enhance microbial respiratory activity. This process shifts the microbial community toward a higher proportion of bacteria relative to fungi, negatively impacting soil carbon storage. Plant functional groups (PFGs) facilitate the release of labile organic carbon from soils and accelerate the rate at which microorganisms mineralize carbon.

When evaluating how agroecosystem multifunctionality (EMF) responds to these changes, both microbial diversity and their interactions must be considered—this is key for forecasting shifts in ecosystem functions under future climate scenarios. Gaining a comprehensive understanding of the climate-microbe-SOC relationship from multiple angles will help maximize the soil's carbon sequestration potential amid global changes.

Keywords

soil organic carbon, global warming, CO_2 levels, plant functional groups, ecosystem multifunctionality

1. Introduction

Global food security faces challenges from climate warming and population growth. Soil degradation associated with intensive agriculture has reduced land available for food production. The far-reaching impacts of climate warming, combined with the urgent need to increase food production, demand climate-adaptive land management approaches that simultaneously boost productivity and facilitate climate change adaptation and mitigation. The UN's sustainable management strategy known as "conservation agriculture" has been widely promoted as a nature-based solution to maintain food production while enhancing soil health.

Since the Industrial Revolution, excessive emissions of greenhouse gases such as CO_2 have caused a continuous rise in global average temperatures, leading to severe consequences like biodiversity loss. Global ecological environmental issues characterized by "climate warming" have become a consensus and critical challenge worldwide, affecting both natural ecosystems and human societal survival and development. Over the past decade, rapid global warming has posed a major threat to global food security. According to the IPCC Sixth Assessment Report, ongoing global warming reduces crop yields and negatively impacts crop biomass, which directly provides essential food calories for humans and indirectly supplies protein through animal feed. By 2050, the global population is projected to reach 10 billion, with global food demand expected to increase by approximately 56% compared to 2010. Given the irreversibility of climate change, understanding how climate change affects crop biomass is imperative to ensure global food security; declining crop biomass due to global warming will make meeting future food demand increasingly challenging.

Conservation agriculture, which includes reduced or no tillage, permanent soil cover, and diverse crop rotation, is applicable to various agricultural environments. Its implementation has yielded extensive environmental benefits, including improved soil health associated with increased SOC storage and soil biodiversity, leading to its adoption in one-third of countries on 12.5% of arable land. However, uncertainties remain regarding its effectiveness under different future climate projections due to the lack of systematic and quantitative assessments of climate warming's long-term impacts on conservation agriculture's ability to support soil health and crop production potential. Field trials specifically comparing conservation agriculture with conventional management under warming conditions are particularly scarce, yet there is an urgent need to explore interactions between management practices, warming, crop yields, and soil health. SOC serves as a "primary" soil health indicator, supporting multiple soil functions such as nutrient and water cycling and retention, soil structure formation, and ecosystem productivity. Climate warming is expected to increase global SOC loss by accelerating microbial decomposition. Additionally, rising temperatures may enhance microbial nitrogen mineralization, altering nitrogen flows in terrestrial ecosystems. In contrast, crop residue retention in conservation agriculture directly promotes SOC accumulation by increasing plant biomass input, alleviates crop water and nutrient limitations through improved soil health, and indirectly accelerates microbial turnover and necromass accumulation by supplying organic matter. Soil conditions created by conservation agriculture can offset the negative impacts of climate change on food production in some regions. To better understand the dynamic balance between soil carbon output and input under global warming and explore microbial response mechanisms, this study reviews the effects of climate warming on SOC transformation and microbial community composition, and proposes prospects to advance related research.

2. Impacts of Climate Warming on Microbial Diversity

Current research primarily focuses on how changes in annual average temperature and precipitation affect crop yields. However, recent studies indicate that winter temperatures in northern mid-to-high latitudes are rising at a rate exceeding 0.5°C per decade. The IPCC (2013) report projects that by the end of the 21st century, the global average surface temperature will increase by 1.8–4.0°C, nearly 1.8 times the rate of annual average temperature rise, particularly in high-latitude regions. Winter warming disrupts crop dormancy, advances phenology, shortens growing seasons and photosynthetic activity, increases the risk of winter crop yield reduction, and elevates the abundance of pests and pathogens. Research on how winter warming affects non-winter crops is limited, but it is important to note that winter warming alters soil temperature and moisture, thereby influencing soil fertility and crop growth. Since 1850, human activities have caused a 1.1°C rise in global surface temperatures, intensifying the global hydrological cycle and changing precipitation patterns. Given the importance of temperature and water for sustaining life, climate change is likely to profoundly impact biodiversity across all levels, from species to entire biomes. Changing environmental conditions may force species out of their climatic niches, reducing their resistance, adaptability, and increasing extinction risks. Ignoring complex trophic relationships between species and functional groups in ecological communities may underestimate climate change's impacts on biodiversity and ecosystem functions. As key components of terrestrial ecosystems, soil microorganisms play vital roles in regulating ecological processes, including nutrient cycling, pathogen control, and plant productivity.

Soil microorganisms drive key processes in agroecosystems, are sensitive to climate change, and are prerequisites for optimizing soil health and crop productivity. The quantity, diversity, activity, and beneficial functions of soil microorganisms contribute to soil health, including effective accumulation and stabilization of soil organic carbon, and crop productivity. Reduced tillage in agricultural production supports the development of mycelial networks and more diverse and abundant soil bacterial and fungal biomass, which aid multiple soil ecosystem functions such as improved substrate and plant nutrient availability. The impact of climate warming on the observed benefits of conservation agriculture for soil microbiota is unpredictable; in warm forest and grassland soils, strong environmental filtering negatively affects fungal and bacterial diversity. Short-term warming significantly increases the abundance of Streptomyces and Gaiella in black soil bacteria. Compared to short-term warming experiments, long-term warming may have different effects on soil microbial properties. After one year of warming in undisturbed temperate heathlands, soil fungal abundance decreased significantly. Studies on eight alpine soils under warming treatments found that the relative abundance of genera with common traits such as heat adaptation, high growth rates, and stress resistance—including Burkholderia and Phenylobacterium—significantly increased.

Soil respiration is sensitive to temperature changes; some large-scale data analyses have found that soil respiration increases significantly by 9%–12% under warming. Research using amplicon sequencing and phospholipid fatty acid analysis to study the effects of long-term drought on forest soil microbial communities showed that bacterial community α-diversity and biomass decreased significantly, while fungi were unaffected. Additionally, studies have found seasonal differences in arbuscular mycorrhizal (AM) fungi—symbionts with plant roots—in terms of infection rate, spore density, and diversity, suggesting that warming-induced enhancement of root nutrient acquisition may reduce mycorrhizal dependence and AM fungal diversity. Under warming conditions, soil-borne plant pathogens may increase, which is noteworthy in crop production systems, although improved soil health supporting crop growth may help offset disease threats. Overall, significant uncertainties remain regarding how soil microbiomes respond to interactions between warming and crop management practices, and their impacts on soil health and crop yields.

3. Impacts of Climate Warming on Soil Carbon Pools

As the cornerstone of soil fertility, soil organic matter affects crop biomass by maintaining soil moisture and nutrient availability, thereby promoting root development. The temperature sensitivity of organic matter decomposition (Q10) is a key parameter for predicting soil carbon fate under global warming; changes in soil Q10 values reflect the response of organic carbon mineralization rates to temperature changes. Studies have shown that winter warming can stimulate soil respiration by increasing soil temperature and altering soil moisture dynamics, thereby accelerating the decomposition of soil organic matter (SOM). The impact of winter warming on soil temperature and moisture may vary with latitude, exerting different effects on soil respiration in different regions. In high-latitude areas, although no crops are grown in winter, intensified winter warming may affect subsequent crop growth through soil-mediated processes. Considering the involvement of soil processes, further research into the mechanisms by which winter warming affects crop biomass is necessary.

Microorganisms drive organic carbon cycling and play two key, opposing roles in influencing carbon content: promoting carbon release into the atmosphere through catabolic activities, and preventing carbon loss by fixing organic carbon into recalcitrant forms. There is a growing recognition that soil microorganisms can play dual roles in mediating terrestrial carbon cycling: microbial catabolism releases soil carbon into the atmosphere, while microbial anabolism produces a range of products that help stabilize soil carbon pools. Both processes are affected by climate warming, and the direction and magnitude of their changes determine soil carbon dynamics in a warmer world.

SOC, the largest organic carbon pool in terrestrial ecosystems (exceeding the sum of organic carbon in vegetation and the atmosphere), plays a crucial role in global nutrient cycling and is significantly influenced by agricultural activities. SOC is continuously input into soils during plant lifecycles, including: 1) root exudates (rhizo-C) from underground plant roots; and 2) straw (straw-C) from aboveground plant biomass. Soil microorganisms are activated and regulated by input crop root carbon and straw carbon. Rhizosphere microbial communities largely depend on the quantity and quality of rhizodeposits released by roots. Plant-derived, easily degradable carbohydrates undergo a series of microbially mediated processes in soils, including energy-producing mineralization (catabolism) and incorporation into microbial biomass (anabolism). Subsequent death and lysis of microbial cells, along with the release of non-biomass metabolites (e.g., extracellular enzymes, extracellular polymeric substances, signaling molecules, and antibiotics), produce various organic cellular compounds, including cell envelope fragments and small biopolymers. These compounds can resist utilization by subsequent microorganisms, bind to minerals, and contribute to the formation of slowly cycling organic carbon pools. Termed microbial-derived carbon (MDC), this fraction originates from microbial necromass. Compared to plant-derived carbon, MDC has more recalcitrant chemical structures and greater affinity for minerals and metal oxides, making it a key component of long-term stable SOC pools. It accounts for approximately half of total organic carbon and is a dynamic ecosystem component influencing climate feedbacks. Long-term comprehensive assessment of MDC storage dynamics is critical for predicting soil carbon storage under future climate scenarios.

4. Impacts of Climate Warming on Soil Nutrients

Human nitrogen and phosphorus deposition significantly affects soil carbon cycling; the impact of nitrogen and phosphorus inputs on soil carbon-climate feedbacks is typically characterized by the temperature sensitivity (Q10) of organic carbon decomposition. Studies have shown that nitrogen and phosphorus inputs can significantly alter organic carbon decomposition in various ecosystems; inconsistencies in previous site-level observations may be attributed to differences in climate and geographical conditions between studies. In warm regions with low initial nutrient levels, soil microbial respiration generally responds more strongly to nitrogen inputs than in cold regions with higher initial soil nutrient levels. The spatial impact of nitrogen and phosphorus inputs on Q10 remains unstudied, but exploring this across broad geographical scales is crucial for accurately assessing the impact of nitrogen and phosphorus deposition on soil carbon budgets under future warming.

Atmospheric nitrogen and phosphorus deposition have increased sharply over the past few decades and are projected to continue rising, becoming a scientific and political concern for human society. The impacts of global change biology on aboveground processes (e.g., biomass production and plant traits) in response to nitrogen and phosphorus deposition are well characterized, but uncertainties remain regarding the response of belowground soil carbon processes (e.g., soil carbon decomposition). Even small changes in organic carbon decomposition processes caused by nitrogen and phosphorus deposition can lead to substantial changes in atmospheric CO_2 concentrations. Therefore, better understanding nutrient-induced changes in organic carbon decomposition under climate change is critical for comprehensively assessing the impact of nitrogen and phosphorus deposition on ecosystem processes.

The main sources of soil carbon are aboveground litter and underground root inputs; carbon output processes primarily involve soil respiration, including root autotrophic respiration and heterotrophic respiration. Warming may affect almost all processes of soil carbon input and output directly or indirectly. It is generally believed that warming accelerates soil organic matter turnover and promotes soil respiration, thereby forming a positive feedback to global warming. However, warming may also increase soil nitrogen availability, thereby enhancing aboveground productivity and offsetting carbon losses from soil respiration. If the rate of plant carbon input is slower than soil respiration, soil carbon storage may decrease. Meanwhile, new carbon input through litter may further promote the decomposition of old soil carbon (the priming effect), gradually increasing net losses from soil carbon pools. Additionally, because soil organic matter is more stable than fresh litter, warming may not affect old carbon decomposition, with microorganisms preferentially decomposing new carbon input by plants; this could mean warming increases plant carbon input and soil respiration without affecting soil carbon pool storage.

Soil nitrogen mineralization and nitrification are key factors influencing forest carbon sequestration. Climate warming may promote soil organic matter decomposition and nitrogen mineralization, increasing soil supply of nutrients such as nitrogen, phosphorus, and potassium to plants, thereby enhancing plant productivity and carbon sequestration. Since fungi and bacteria occupy different ecological niches in soil environments, some studies suggest that warming may favor bacterial growth while inhibiting fungal growth, with certain selectivity for soil microbial functional groups. Microbial communities are more sensitive to environmental changes than individual trees; thus, warming may promote soil nitrification and denitrification, increasing gaseous nitrogen loss from soils and reducing nitrogen acquisition by plant roots. Warming studies in forests and grasslands have identified common changes in microbial community composition, including decreased fungal-to-bacterial ratios and increased abundance of Gram-positive bacteria; bacteria have competitive advantages over fungi in growth rate and nutrient acquisition. Additionally, warming is often accompanied by increased soil moisture evaporation; for organic matter decomposition and nitrogen mineralization, reduced soil moisture will offset part of the warming effect, potentially weakening tree growth responses to warming, or even inhibiting growth in ecosystems with low soil moisture.

5. Relationship Between Agroecosystem Multifunctionality and Microbial Diversity

The relationship between agroecosystem functions (EMF) and microorganisms has long been a focus of ecologists, driven by the need to understand how biodiversity loss under global change affects ecosystem functions, services, and human well-being. Soil biodiversity plays an important role in supporting multiple ecosystem functions and services, including soil nutrient cycling, carbon storage, and erosion control; plant diversity influences soil microbial activity, carbon storage, and nutrient supply, thereby enhancing soil fertility and plant productivity.

The relationship between soil and plant biodiversity and their functions depends on the environment, but the biological and environmental factors shaping this relationship are not well understood. The impact of soil biodiversity on functions may depend on ecosystem water availability; the influence of plant species on soil bacterial communities depends on plant community diversity and is regulated by the effect of plant resources on antagonistic soil microorganisms. Temperature is a key factor affecting plant growth and metabolism; complementarity between plant and soil microbial diversity contributes to environmental multifunctionality, but these contributions are influenced by environmental changes, highlighting the importance of microbial diversity in shaping positive relationships between plant diversity and ecosystem functions.

Multifunctionality is a comprehensive ecological concept, often used to assess an ecosystem's ability to provide multiple functions simultaneously, especially under global change scenarios. Ecosystem functions are positively correlated with species diversity, which may be attributed to niche complementarity, positive interactions, and reduced abundance of pathogenic species. Driven by the "warming" effect, some native plant species that respond rapidly to temperature changes tend to decline, while other plant species begin to expand, altering interspecific relationships, community structure, and distribution patterns of plant species, and profoundly affecting ecosystem functions and stability centered on plant diversity. Previous studies have focused on bacteria and fungi, largely neglecting protists. As predators, heterotrophic protists play important roles in controlling bacterial and fungal populations and nutrient cycling, and affect ecosystem multifunctionality. To better understand future ecosystem multifunctionality, a comprehensive assessment of bacteria, fungi, protists, and their potential interactions is needed. Since the direct impact of global change on soil microbial community diversity may be limited, plant-microbe interactions play a key role in regulating terrestrial ecosystem responses to environmental changes. Climate change-induced changes in plant community characteristics indirectly affect microbial community composition and metabolic functions by altering the quantity and form of soil carbon inputs. Studies have shown that increased precipitation affects positive feedback between plants and microorganisms; increasing vegetation diversity can mitigate the long-term impact of drought on microbial communities and enhance microbial community tolerance to drought stress. Different microbial groups are highly interconnected through predation, symbiosis, and competition, which can be explored through co-occurrence network analysis. Network attributes such as edges, nodes, and average degree are common indicators for assessing interactions and network complexity among microbial groups, and have been used to model microbial networks and their responses to climate change. Climate warming can enhance microbial network complexity and may affect ecosystem functions and services; precipitation can also strongly influence the network complexity of arbuscular mycorrhizal fungal (AMF) communities by altering interactions among AMF groups.

6. Conclusion

Predicting the effectiveness of conservation agriculture under climate warming is challenging due to complex interactions between climate warming and soil management on crop yields and soil properties. Overall, climate warming profoundly affects agricultural activities in many ways, from yield reductions to losses of organic carbon and ecosystem functions. Rising temperatures lead to crop yield reductions, which in low-latitude regions are mainly caused by drought, disrupted crop growth cycles, and increased pathogen pressure. Organic carbon is a "primary" soil health indicator, supporting multiple soil functions including nutrient and water cycling and retention, soil structure formation, and ecosystem productivity. Climate warming accelerates microbial decomposition, enhances microbial nitrogen mineralization, reduces phosphorus uptake, and causes nitrogen and phosphorus loss in terrestrial ecosystems, thereby increasing global organic carbon loss. Metagenomics provides a powerful tool for revealing microbial community structure and function and their relationships with environmental factors, laying the foundation for exploring the evolutionary characteristics and metabolic capabilities of different microbial communities under climate change. Sufficient awareness of the impact of global climate change on soil microorganisms is essential. Crop residue retention in conservation agriculture directly promotes organic carbon accumulation by increasing plant biomass input to the soil surface, alleviates crop water and nutrient limitations by improving soil health, and indirectly accelerates microbial turnover and necromass accumulation through organic matter supply. Climate warming has both direct and indirect impacts on microbial community composition and activity, but studies on their interactive effects are limited, hindering our understanding of SOC response and feedback mechanisms under climate warming. Additionally, climate zones, seasons, and extreme climate events have important impacts on EMF under global warming, which should be addressed in future research to more accurately predict soil carbon source responses and feedbacks to climate warming.

7. Prospects

Due to limitations in research methods, current understanding of soil carbon cycling processes in response to climate warming remains controversial, and much of this understanding is based on short-term simulated warming experiments, which cannot provide reliable support for accurate predictions of climate change processes. Therefore, long-term in-situ and isotope labeling experiments targeting these controversies, along with continuous exploration of new research methods, are key directions for future research in this field. Specific aspects include:

a) Soil microorganisms play key roles in soil carbon cycling and nutrient transformation, and are sensitive to climate change. However, existing climate change prediction models do not incorporate soil microbial processes; many models simply relate soil organic carbon decomposition to the size of soil carbon pools based on greenhouse experiments, preventing important research findings in soil microbiology from being applied in climate change models. Therefore, it is necessary to link soil organic carbon decomposition processes with soil microbial processes and integrate them into climate change models.

b) Current understanding of soil microbial composition, structure, and functional traits remains vague, with most attention focused on bacteria and fungi, and limited exploration of protists and nematodes. However, soil microorganisms are diverse and functionally distinct, and many are unculturable. These issues pose significant challenges to traditional research methods; thus, actively exploring new research methods is the main approach to address these challenges.

c) Climate change, marked by global warming, affects soil carbon cycling through multiple processes such as elevated CO_2 concentrations, altered precipitation, and nitrogen deposition. Current research mainly focuses on isotope labeling and DNA-SIP, lacking comprehensive studies of overall metagenomics and metabolomics. Therefore, when studying the impact of climate warming on soil carbon cycling processes, multiple research methods should be used to investigate the combined effects of multiple climate change factors.

d) Aboveground and underground components of soils form an interactive organic whole; their interactions jointly affect soil carbon budgets and cycling processes. Therefore, when studying soil carbon cycling responses to climate warming, it is necessary to systematically consider the responses of overall ecological processes in aboveground components and underground components (bare soil, rhizosphere soil, deep soil) to climate warming.

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