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Review

Potential Effects of Climate Change on Soil Properties

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Abstract

Climate change is one of the most critical drivers altering soil processes and disturbing agroecosystem sustainability worldwide. Rising temperatures, shifting precipitation patterns, and more frequent extreme weather events directly and indirectly affect soil properties. Specifically, climate change impacts soil fertility by accelerating organic matter decomposition, increasing salinization and acidification risks, disrupting nutrient cycles, and undermining microbial activity and soil structure. These changes collectively reduce soil resilience and productivity while intensifying greenhouse gas emissions from soils. This article reviews current knowledge of these impacts and highlights Mitigation strategies such as conservation agriculture, improved nutrient and water management, crop diversification, and soil carbon sequestration to enhance soil stability. This article reviews current knowledge of these impacts and highlights Mitigation strategies such as conservation agriculture, improved nutrient and water management, crop diversification, and soil carbon sequestration to enhance soil stability.

Keywords: Climate change, Soil health, Soil properties.

Introduction

Soil is composed of organic materials, minerals, liquids, gases, and microbes. Because it serves as a medium for plant growth, stops water loss, and offers a home for a variety of microorganisms, soil is essential to the environment. In addition, the vegetation is directly impacted by the fertility of the soil. The term "soil biota" refers to a variety of microorganisms, including nematodes, insects, earthworms, bacteria, fungi, and algae [1]. Microorganisms, a component of the soil biota, are essential to the regulation of biogeochemical transformation. The turnover and production of soil organic matter (mineralization and C sequestration), nutrient cycles, disease transmission and prevention, pollution reduction, and soil structure enhancement are among the main tasks carried out by soil biota [2].

Soil organisms have an impact on the structure of the soil because they bind soil particles together, increasing the quantity and size of mass that encourages the habitat of microfauna. Greenhouse gases like carbon dioxide ($CO2$), methane ($CH4$), and nitrous oxide ($N2O$) are formed as a result of the oxidation and reduction of C and N molecules in soil.

Physical, chemical, and biological traits are examples of soil attributes. The physical characteristics of soil provide information on the flow of water and air

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through the soil (as well as factors influencing germination, root growth, and soil erosion processes). Climate, landscape location, and land use patterns can all have an impact on these physical characteristics, which are closely related to the chemical and biological characteristics of soil [3]. The physical characteristics of soil, including its structure, water infiltration, density, rooting depth, and surface cover, can be influenced by the climate. pH, electrical conductivity, sorption, cation exchange capacities, and accessible plant nutrients are some of the chemical characteristics of soil. The primary indicator of soil health, pH, is affected by weathering time, vegetation, and climate. It can be used to detect changes in the biological and chemical functions of soil (acidification, salinization, crop performance, nutrient availability, and biological activity). Soil biota, which includes soil organic matter, soil carbon, light fraction, macro-organic matter, potential C and N mineralization, soil respiration, soil microbial biomass, and enzymatic activity, is the basis for evaluating the health of the soil. The ability of soil to support life (plants, animals, and humans) is referred to as soil health or soil quality, according to the USDA. Since soil contains microorganisms that improve its ability to produce food and fiber, it needs food, shelter, and water to be nourished and healthy. According to Allen [3], the physical, chemical, and biological properties of soil serve as markers of soil health and can be impacted by changes in the surrounding environment and climate.

A change in weather patterns that directly impacts food production (agricultural effect) and raises sea levels (causing floods) is referred to as climate change. Global warming, or an increase in temperature brought on by greenhouse gases, is not the same as climate change. Climate change has the ability to affect nearly everything. Sea ice loss, sea level rise (1–8 feet by 2100), extreme heat waves, altered precipitation patterns, stronger hurricanes, and an increase in droughts (due to longer summers) are some of these effects, according to the UN. According to IPCC forecasts, greenhouse gases (produced by human activity) will cause temperatures to rise by 2.5 to 10°F over the course of the next century.

Impact of Climate Change on Soil Properties

Physical Properties: The characteristics of soil that are related to the size and arrangement of soil particles are known as its physical attributes. It also considers how the size and distribution of solar particles affect the flow of liquids and gases through it. This comprises soil structure, texture, and dynamic properties such as bulk density, porosity, infiltration, and water-holding capacity. Soil fertility is influenced by the biological (biological activity, nutrient supply, adsorption, water, and heat movement) and chemical processes that are greatly influenced by the physical properties of the soil.

Theoretically, variations in temperature and precipitation can lead to four situations:

(a) lower temperature with less precipitation
(b) A higher temperature with less precipitation
(c) A higher temperature with more precipitation
(d) lower temperature with more precipitation

1. **Soil Texture:** The texture of the soil is the most significant and fundamental feature that determines its qualities. It is described as the size of the mineral particles or the correlated ratios of various mineral size groups found in a particular soil sample. There are three different types of soil texture: sand, silt and clay.

   Because soil texture changes relatively slowly in accordance with the geologic time scale, it is not vulnerable to change over time and is therefore not very important to study of climate change. Nonetheless, it continues to be an important factor in determining how sensitive soil is to climate change.

However, this soil type was susceptible to climatic changes due to the phenomena of clay soil shrinkage and cracking in response to an increase in drying and wetting cycles. Significant soil crack growth is the outcome of this. Deep fissures can weaken the soil's filtering mechanism, increasing the danger of nutrient loss and water contamination. This is why water flows directly and quickly from the soil's surface through the bypass flow (or drainage pipes). These processes are typical in clay soils, but when there are frequent droughts followed by periods of heavy precipitation, more material and water are lost.

2. **Structure: Shape and Stability:** Pore size and porosity, together with soil stability (structure) and size, are the primary determinants of soil aeration and moisture status. The soil's capacity to store water can be directly impacted by changes in soil porosity, which can also alter the soil's emissions of carbon dioxide (aerobic state) and methane (anaerobic condition). The raindrops have a direct impact on the soil aggregate. As a result of rising temperatures and decreased water availability, soil aggregate stability and size diminish when soil organic and biomass content decreases.
3. **Porosity and Bulk Density:** It has been a highly complicated process to alter soil shape, structure, and spatial distribution while maintaining soil aggregate stability in relation to climate change. Through processes of dispersion, slaking, compaction, and mechanical disruption, temperature increases and variations in the temporal distribution and volume of precipitation directly affect soil structures.

   Climate is known to have an impact on bulk density, which is strongly related to soil textural characteristics and organic matter quality. The pace of soil erosion or decomposition causes a rise in bulk density, which leads to the loss of organic matter in the soil and compaction with all of its consequences, including the obstruction of root growth due to the formation of a compact layer and a decrease in soil porosity.
4. **Soil Organic Carbon:** The impact of the soil's organic carbon content on water is determined by the ratio of the soil to its organic carbon concentration. Walter conducted an experiment to examine the impact of climate change on the pace of decomposition in temperate grasslands.

   As a result, the rate of decomposition slowed down after litterbags were subjected to drought conditions for roughly six weeks. This demonstrated that decomposition was more vulnerable to climate change or drought. The makeup of soil bacterial communities and decomposition processes can be significantly changed by severe droughts. It was discovered that the rate of litter mass loss is reduced by 5% in relation to the exposure period, even in the case of a very brief drought combined with intense rainstorms.

   Changes in soil temperature or humidity, as well as the makeup and functioning of soil and microbial communities, all contribute to climate change. These changes have a direct impact on soil biological activities, which alter decomposition processes. Therefore, in more intensively maintained grasslands, drier climate conditions brought on by global warming may decrease nutrient cycling and change the soil's carbon balance. Decomposition is significantly impacted by changes in climatic conditions because they alter the biotic behavior of the soil rather than the amount of trash.

Soil Chemical Properties: Some of the most important soil chemical characteristics include pH, carbonate concentration, and other nutrient contents and their distribution in the soil profile, soluble salt content, base saturation, and cation exchange capacity (CEC).

1. **Soil pH:** Since the parent material, climate, vegetation, and rate of weathering all affect soil pH, direct climate change influences are unlikely to cause it to change quickly. Conversely, increased precipitation can worsen leaching and lead to acidity of the soil.

   In well-drained, structurally sound soil that receives a lot of rain, low pH levels can mobilize hazardous ions and cause heavy metal leaching. Soil acidification is the cause of the alterations in soil chemistry.

   In a 1955 study, Crocker and Major examined the evolution of glaciated soil surfaces over time as a result of surface age and vegetation. According to the estimated 50-year changes, the pH of the soil will drastically decrease if vegetation starts to grow, while the pH shift on a bare soil surface will be insignificant for decades [4].
2. **Salt Content:** While $Ca^{2+}$and Mg^{2+} are more common in neutral and somewhat alkaline soils, high amounts of H^+ and Al^{3+} may be present in extremely acidic soils. It is crucial to understand how absorbed cations impact soil aggregate structure formation and, consequently, soil water management. While calcium can maintain and shield the aggregate structure of salt-affected soils, the high concentration of sodium in the adsorbed cations results in a weak, diffuse structure. Saline structured soils with different Na^+ and Ca^{2+} solutions and SAR values were investigated by David and Dimitrios in 2002.
3. **Electrical Conductivity:** The concentration of salt is measured by the electrical conductivity (EC) of the soil. It can reveal patterns in biological activity, the nitrogen cycle, crop performance, and salinity. It can serve as a stand-in indicator of soil structural deterioration in addition to pH, particularly in sodic soils [5]. As a chemical biomarker of soil biological quality in response to crop management techniques, electrical conductivity has been employed [6]. Increasing temperatures and decreasing precipitation increase the electrical conductivity under climate change scenarios [7]. A non-linear relationship between the soluble salt content and rainfall was discovered in the dynamics of soluble salt concentration in soils from four climatic regions (Mediterranean, Semi-arid, Mildly Arid, and Arid). Sites that received less than 200 mm of rainfall had significantly higher soluble contents, and vice versa.
4. **Sorption and Cation Exchange Capacity:** Sorption and cation exchange capacity (CEC) are regarded as crucial characteristics, especially the immobilization of potentially hazardous cations Al^{3+} and Mn^{3+} and the retention of major nutritional cations Ca^{2+}, Mg^{2+}, and $K^{+.}$ According to Ross [8], these characteristics can therefore be helpful markers of soil health that reveal a soil's ability to absorb pollutants, herbicides, and nutrients. Since SOM is responsible for the CEC of low-activity clay soils and coarse-textured soils, the increasing decomposition and loss of SOM brought on by high temperatures may cause these soils to lose their CEC [9]. Alkalinity may be transported from soil to waterways as a result of enhanced base cation leaching in response to heavy rainfall events.
5. **Cycle of Nutrients:** It is important to keep in mind that one of the nutrients in the soil that is directly connected to the water cycle is nitrogen. The chemical characteristics of the soil determine its biological and physical behavior as well as its interactions with biological and physical soil processes. They use biological activity and soil pH monitoring to assess the fertility and nutrient regime of the soil. Nutrient availability will therefore be impacted by factors that affect both the carbon cycle and the water delivery cycle. An increase in yearly rainfall speeds up the loss of carbonate in the soil profile, and one of the key elements in carbonate leaching is percolation [4].

Increased yearly precipitation will accelerate leaching and down-flooding, increasing acidity. Toxic substances (such as heavy metals) will become more mobilized as a result of acidification, creating harmful and inhospitable conditions for plants and other living things. Soil acidification caused by human CO_2 release was examined by Kopittke [10]. Both control and drought event scenarios were replicated during the germination phase in the summer. The pH of the soil solution was lower than that of the control plot in both treatments. Nevertheless, compared to the treatment plots, the control plots' soil solution pH was more acidic. The ozone hole has clearly been inhibited by the drought.

Widespread secondary salinization could be caused by improper irrigation techniques and an increase in irrigation water demand. Upward capillary transmission is important in recent areas where shallow groundwater is the source of salt and reductions are needed. The potential effects of climate change on soil characteristics would be lessened, which would mean that fewer soluble salts would be carried to the surface.

6. **Soil organic matter:** A wide variety of living and non-living elements make up soil organic matter (SOM), which is one of the most intricate and diverse elements of soils with a wide range of characteristics, functions, and turnover rates [11]. It contributes to the charge properties of soils, acts as a source and sink for carbon and nitrogen, and to varying degrees, controls the cycling of phosphorus and sulfur. It can combine with organic molecules and multivalent ions to create complexes. It influences aggregate stability, water retention, and hydraulic qualities in addition to providing microbiological and faunal habitat and substrates [11&12]. Since SOM is the primary driver of most soil processes, reductions in SOM can result in decreased fertility and biodiversity as well as a loss of soil structure, which lowers the soil's ability to hold water, increases the danger of erosion, increases bulk density, and ultimately causes soil compaction.

Soil Biological Properties

1. **Soil Carbon and C:N ratio:** Microbial activity, mineralization/decomposition, is stimulated by elevated temperature and sporadic rainfall. Reduced biomass accumulation, soil carbon depletion, and a lower C:N ratio will result from this [13,14&15]. Plant water usage efficiency rises with increased atmospheric CO2. According to Kimball [16], it will boost biomass production per millimeter of available water. When there is a greater water deficit, the rate of decomposition is higher than the net primary productivity. This method results in a drier environment that is ideal for the reduction of organic carbon. Biomass losses brought on by drought decrease both annual and perennial plants. Conservation tillage techniques, crop residue management, green manuring, and intercropping are examples of management techniques.
2. **Soil Respiration:** Soil respiration is used as a biological indicator for soil health, since it is positively correlated with SOM content. One important connection between climate change and the global carbon cycle is soil respiration, specifically its temperature sensitivity [17]**.** Changes in the seasonal timing of rainfall have a rather significant impact on soil respiration.
3. **Enzyme Activity:** Because soil enzyme activities are closely related to the cycling of nutrients and soil biology are easily measured indicators that integrate information on both the microbial status and the physicochemical conditions of soil. These indicators exhibit a rapid response to changes in soil management practices and therefore can be effectively used to signal shifts and alterations within the plant–soil system [18].

Additionally, increased CO2 may increase microbial enzyme activity, microbial enzyme abundance, and C turnover, thereby impacting the functioning of the microbial community in soil by changing the amount and quality of below-ground C input by plants. The role of soil microbial enzyme activity on organic carbon turnover, nutrient cycling, and greenhouse gas emissions is still unknown.

Adaptation and Mitigation Strategies

1. **Climate Change Adaptation in Agriculture:** Agriculture can adapt to climate variability and extreme weather events by adopting farm management practices that minimize the adverse impacts of altered rainfall patterns, rising or declining temperatures, and climatic extremes.
2. **Conservation-based Management Practices:** The adoption of zero or reduced tillage helps improve soil structure and enhance moisture conservation, while the retention of crop residues minimizes evaporation losses and buffers soil temperature. Additionally, extending fallow periods contributes to the restoration of soil moisture and fertility, thereby supporting long-term soil health and sustainable crop production.
3. **Diversification and Cropping System Adjustments:** Increasing crop and varietal diversity enhances the resilience of the production system, while the inclusion of climate-resilient crops and diversified crop rotations helps reduce climate-related risks and stabilizes productivity under variable environmental conditions.
4. **Optimization of External Inputs:** Adjustments in the amount and timing of fertilizer application and irrigation based on prevailing climate signals, along with efficient water and nutrient management practices, help minimize losses and improve resource-use efficiency under variable and changing climate conditions.
5. **Agronomic Management Interventions:** Modification of planting density and row spacing can optimize the use of available resources, while altering planting dates helps crops avoid periods of heat or moisture stress. In addition, the introduction of heat-, drought-, and stress-tolerant germplasm supports crop adaptation and sustains productivity under changing climatic conditions.
6. **Agriculture as a Climate Change Mitigation Tool:** Agricultural systems can contribute significantly to climate change mitigation through practices that reduce greenhouse gas (GHG) emissions and enhance soil carbon sequestration.
7. **Reduction of Carbon Dioxide (CO_2) Emissions:** Minimization of biomass burning and improvement in energy-use efficiency in farm operations contribute to reduced greenhouse gas emissions, enhanced environmental sustainability, and more climate-friendly agricultural production systems.
8. **Mitigation of Methane (CH_4) Emissions:** Improved management of livestock waste and optimized water management in flooded rice ecosystems help reduce greenhouse gas emissions, enhance nutrient recycling, and promote more sustainable and climate-resilient agricultural systems.
9. **Reduction of Nitrous Oxide (N_2O) Emissions:** Improved nitrogen fertilizer management through the use of appropriate fertilizer types, application rates, timing, and methods, along with the adoption of soil management practices that prevent soil compaction and enhance soil aeration, can significantly reduce nitrogen losses, improve nutrient-use efficiency, and support sustainable crop production.
10. **Enhancement of Soil Carbon Sequestration:** Conservation agriculture practices that encourage the buildup of soil organic matter, combined with long-term soil health management strategies, support sustained carbon storage, enhance soil

fertility, and contribute to climate change mitigation and sustainable agricultural productivity.

Soil carbon reserves can be increased, and soil functional stability can be promoted by a variety of farm management techniques. By creating a protective soil cover and an environment that supports vigorous plant growth, conservation agriculture technologies (minimum soil disturbance, cover crops, and crop rotations including legumes), soil conservation techniques (such as contour farming), and nutrient replenishment strategies can restore soil organic matter.

The global soil carbon pool is four to five times bigger than the biomass pools. This doesn't even take into account that soil deterioration in the last several years has caused losses of 30% to 75% of their previous soil organic carbon. Therefore, an increase in soil carbon has significant mitigation potential on a global scale. The storage of carbon in a stable solid state is known as carbon sequestration. It happens when atmospheric CO2 is fixed both directly and indirectly. Inorganic chemical processes that transform CO2 into soil inorganic carbon molecules, like calcium and magnesium carbonates, provide direct soil carbon sequestration. As plants convert atmospheric CO2 into plant biomass through photosynthesis, direct plant carbon sequestration takes place.

Role of Policy and Technology

The Challenge: International cooperation is necessary to address the global issue of climate change. Nearly all countries, including the United States, have accepted the UN Framework Convention on Climate Change (UNFCCC), which aims to stabilize greenhouse gas (GHG) concentrations at levels that avoid hazardous anthropogenic (human-induced) interference with the climate system, United Nations (1992) [19]. In order to achieve the UNFCCC goal, substantial emissions reductions are required in the upcoming decades due to the atmospheric lifetimes of GHGs, which range from 5 to 50,000 years [20].

The Intergovernmental Panel on Climate Change (IPCC) published its Sixth Assessment Report in 2023, detailing the effects of climate change and mitigation and adaptation methods. Global emissions must decrease by 48% from 2019 levels (52.9G t CO2e) by 2030, reach net-zero by 2050, and then become net-negative in order to keep warming to 1.5 ˚C. This necessitates drastic and quick emission reductions in every area [21]. Only 2.6% less than 2019, the most recent Nationally Determined Contributions (NDCs) would produce 48.3–54.7 Gt CO2e in 2030 [22]. As the second-largest polluting nation, the United States generated 11% of global GHG emissions in 2023 with 5.96 Gt CO2e, a 1.4% reduction from 2022 [23].

General Policies

Economic Instruments

Economic instruments reduce emissions by internalizing the societal costs of pollution and allowing firms the flexibility to respond through innovation; these instruments include carbon taxes, baseline-and-credit programs, subsidies, cap-and-trade mechanisms, and clean energy standards. In a cap-and-trade carbon permit system, emission allowances are allocated or auctioned, and entities that emit less than their permitted limit can sell surplus allowances to those exceeding their caps, thereby creating a strong financial incentive for emission reduction [24].

Regulatory Instruments

Regulatory instruments, such as non-tradable permits, technological and performance standards, product bans, and government investment, are requirements implemented by the government that carry financial or legal penalties for noncompliance [25].

Performance standards, which are used in the transportation and energy sectors, specify goals (such as maximum emissions and the percentage of zero-emission production) and permit flexibility in their implementation [25].

Regulatory tools are more efficient at focusing on certain sector goals, but they may be more expensive economically [25].

Voluntary Agreements

Incorporating voluntary agreements, which are negotiated promises between the public and private sectors, into legislation increases the cost-effectiveness of businesses [25].

Through voluntary programs, the U.S. Environmental Protection Agency (EPA) collaborates with several industries to enhance climate change adaptation, promote clean energy, and lower greenhouse gas emissions [26].

The Kyoto Protocol

Aiming for an overall reduction of 5% below 1990 levels by 2012, the Kyoto Protocol, which went into force on February 16, 2005, set binding GHG reduction objectives for UNFCCC countries [27].

Following 2012, a second amendment to the Kyoto Protocol was made, with the new objective being to reduce emissions by 18% below 1990 levels by 2020 [27].

The Paris Agreement

The Paris Agreement, which was ratified by the UNFCCC in December 2015 and went into effect on November 4, 2016, limits the rise in global temperatures to less than 2 ˚Cover pre-industrial levels [28].

By June 2025, 195 of the 198 parties had approved the Paris Agreement [29].

The White House issued an executive order on January 20, 2025, ordering the United States to immediately withdraw from the Paris Agreement and all associated UNFCCC obligations [30].

Conclusion

Climate change significantly degrades soil health by disrupting soil properties, nutrient cycling, and microbial activity, thereby reducing agricultural productivity and ecosystem resilience. These impacts also intensify greenhouse gas emissions, further accelerating climate-related soil degradation. Implementing climate-resilient practices such as conservation agriculture, efficient resource management, and soil carbon sequestration is essential for sustaining soil health and agroecosystem stability.

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