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Transformation in Soil Properties under Changing Climate: Impacts and Dynamics

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Abstract

The chapter explains the profound effects of climate change on soil characteristics and the sustainability of agriculture. India has experienced an increase in events like droughts, floods, and cyclones, exacerbating the challenges posed by climate change. These alterations in weather patterns lead to significant changes in soil physical properties such as texture, structure, density, porosity, temperature, and moisture dynamics within the soil profile. They also affect chemical properties like soil pH, electrical conductivity (EC), cation exchange capacity (CEC), and the cycling of nutrients, all of which ultimately impact soil health and agricultural productivity. Furthermore, climate change influences soil organic matter levels, microbial activity, and the efficiency of nutrient utilization, making agricultural management more complex. These outcomes endanger soil fertility, water retention, and ecosystem stability, posing substantial risks to both agriculture and global food security. To overcome these difficulties and strengthen the ability of soil ecosystems to withstand them, it's essential to adopt measures like sustainable land management, carbon sequestration, and reducing emissions.

Introduction

Climate change, mainly caused by human actions such as burning fossil fuels and deforestation, significantly affects weather patterns and the global environment. These changes bring increased natural disasters, rising sea levels, biodiversity loss, and disruptions to agriculture and food security. Evidence of climate change impacts in India is apparent from numerous studies. The climate of Leh region shows warming trend and decrease in the amount of precipitation (Chevuturi et al., 2018). There is increase in maximum temperature by 1.2°C in west coast, 1°C in northeast, 0.9°C in western Himalaya, 0.6°C in north-west, 0.8°C in north central, and east coast, and 0.5°C in the interior peninsular region of India. In India, the mean atmospheric surface temperature has escalated during winter and post-monsoon months by 1 and 1.1°C, respectively (Dash et al., 2007).

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The minimum temperature is also depicting increasing trend in India. Climate change significantly alters weather patterns and soil health, posing substantial challenges for ecosystems and human activities. The warming climate leads to more extreme weather events, including more frequent and severe storms, heatwaves, and unpredictable precipitation patterns. These changes can result in prolonged droughts in some regions and intense rainfall and flooding in others, disrupting agricultural cycles and water availability. Soil health is also adversely affected, as increased temperatures and altered precipitation can lead to soil erosion, nutrient depletion, and reduced fertility. Notably, 12 out of the 15 hottest years occurred between 2004 and 2018 in India, with an overall increasing trend in annual mean temperature of 0.61°C per 100 years from 1901 to 2019 (IMD, 2020). Furthermore, the frequency of cyclones, particularly in recent years, has increased, with notable events such as super cyclones 'Fani' in Odisha in 2019, 'Amphan' in the Bay of Bengal in 2020, and severe cyclonic storms 'Nisarga' over the Arabian Sea. As reported by Mani et al. (2018) in "South Asia's Hotspots: Impacts of Temperature and Precipitation Changes on Living Standards", increasing temperatures and unpredictable rainfall patterns could reduce India's GDP by 2.8%. Nearly half of South Asia's population, including that of India, lives in regions at high risk where climate change is expected to deteriorate living standards.

Climate change significantly alters natural resources such as soil, impacting various soil properties directly or indirectly. Reports from different climate scenarios — humid, sub-humid, semi-arid, and arid — indicate changes in soil texture differentiation (Brinkman & Brammer, 1990; Scharpenseel et al., 1990). Changes in precipitation patterns induced by climate change affect soil structure through processes like slacking, mechanical disturbance, dispersion, and compaction (Reubens et al., 2007). Elevated temperatures, decreased soil water availability, and reduced organic matter content diminish soil aggregate stability, further altering soil structure (Lavee et al., 1998). Moreover, climate change impacts soil health by affecting microbial activity, root growth, and aggregate stability, consequently altering soil porosity (Patil & Lamnganbi, 2018).

Major impacts of climate change on soil properties

Climate change significantly affects various soil attributes, encompassing physical, chemical, and biological aspects. Characteristics like porosity, moisture retention ability, temperature, cation exchange capacity, and levels of soil organic carbon are notably impacted by climate change.

Soil texture, structure and aggregate stability

Soil texture denotes the fraction of sand, silt, and clay present in the soil, constituting a fundamental soil property that evolves slowly over time and is thus not expected to undergo significant changes within the timeframe relevant to climate change studies. However, despite its gradual nature, soil texture plays a pivotal role in determining a soil's susceptibility to alterations in regional climate conditions (Gelybó et al., 2018). Through the application of the Soil-Vegetation-Atmosphere-Transfer (SVAT) model, Bormann et al. (2012) observed varied responses among soils of different textures to shifts in regional climate parameters, with silt-rich soils demonstrating heightened sensitivity compared to clay-rich soils. Various climate scenarios—such as arid, semi-arid, sub-humid, and humid—have been shown to exert significant influences on soil processes, particularly impacting textural differentiation within the soil profile (Brinkman & Brammer, 1990; Scharpenseel et al., 1990).

Soil structure is the organization of soil particles, affecting physical, chemical, and biological properties. It influences air, water, and agrochemical movement, as well as soil flora and fauna. It's a key indicator of soil health, regulating functions like organic carbon accumulation, water retention, and microbial activity (Patil & Lamnganbi, 2018). The structure of soil is profoundly shaped by various factors including organic matter, inorganic components, cultivation practices, and environmental conditions (Karmakar et al., 2016). Climate change adds layers of complexity to this relationship by altering precipitation patterns and raising temperatures, thereby directly affecting soil structure through processes like slacking, dispersion and compaction (Reubens et al., 2007). Additionally, climate-induced changes such as intense rainfall and shifts in vegetation and land use patterns further impact soil structure and stability (Varallyay, 2005 and 2010; Singh et al., 2011). The disruption of soil aggregates by high-intensity rainfall and the reduction of aggregate stability due to factors like temperature increase and decreased organic matter content exacerbate issues such as compaction, runoff, and erosion (Bot & Benites, 2005; Singh et al., 2011; Karmakar et al., 2016).

Soil bulk density and porosity

Bulk density, also referred to as apparent density, is ascertained by dividing the dry weight of soil by its volume, including both the volume of soil and the volume of pores. Typically expressed in g/cm^3, bulk density plays a key role in soil function, shaping the movement of water, solutes, and gases. The amount of soil organic matter (SOM) generally impacts bulk density, with higher SOM leading to lower bulk density and vice versa. Climate change-induced effects, such as accelerated organic matter decomposition due to rising soil temperatures and increased soil erosion, can elevate soil bulk density, resulting in soil compaction (Davidson & Janssens, 2006; Birkás et al., 2009). This compaction, in turn, hampers root growth, microbial activity, and soil hydrological properties, reducing porosity.

Soil porosity denotes the fraction of soil volume occupied by water and air. Various factors, including bulk density, texture, soil structure, and SOC content, influence soil porosity. Climate change-driven factors such as elevated temperatures, CO_2 levels and extreme rainfall can impact soil health by altering microbial activity, diminishing root growth, reducing aggregate stability, and promoting soil compaction, ultimately affecting soil porosity (Patil& Lamnganbi, 2018). Changes in porosity directly affect soil aeration and the availability of water to plants.

Soil moisture and soil temperature

Soil moisture, the water contained within soil pores, varies both spatially and temporally, affected by variables like climate, soil, topography, and vegetation type (Gwak & Kim, 2017). Soil moisture dynamics, representing temporal changes in soil moisture, are affected by factors like water availability for plant growth, water movement in the soil profile, and evapotranspiration (ET) losses (Gelybó et al., 2018). Climate change events, including temperature increases, altered precipitation patterns, droughts, and floods, significantly impact soil moisture dynamics. Precipitation induces rapid soil moisture changes within hours, while higher temperatures lead to increased evaporation loss from the soil. These dynamics influence available water for plants and can be utilized to evaluate integrated soil health (Karmakar et al., 2016). Holsten et al. (2009) projected that under modelled climate scenarios, a reduction of 4–15% in the average available soil water could occur by the mid-21st century. Utilizing the Soil-Water Atmosphere-Plant (SWAP) simulation model by Van Dam (2000), Hernadi et al. (2009) demonstrated that during years reflecting average weather conditions, chernozem soils would retain significantly less water. The anticipated alterations in rainfall intensity, duration, and distribution may lead to soil water stress.

Soil temperature is significantly influenced by air temperature, as they are closely linked and interdependent. The soil temperature regime is mainly determined by the balance between incoming solar radiation, evaporation from the soil surface, heat conduction through the soil layers and convective movement through water and air (Karmakar et al., 2016).

Table 1: Expected effects of climate change on various soil properties

Soil Properties	Effect	Expected cause
Soil Moisture	Decrease in some regions, increase in others	Changes in precipitation patterns and increased evaporation rates can lead to soil drying or waterlogging.
Soil Temperature	Increase	Higher atmospheric temperatures directly increase soil temperatures, affecting microbial activity and root growth.
Organic Matter	Decrease	Higher temperatures accelerate decomposition rates, reducing organic matter content in the soil.

Soil Properties	Effect	Expected cause
Soil Structure	Degradation	Increased rainfall intensity and drying cycles can lead to soil erosion and compaction, affecting soil structure.
Soil Erosion	Increase	More intense and frequent rainfall events can enhance erosion rates, leading to loss of topsoil.
Soil pH	Variability	Changes in rainfall patterns and acid deposition can alter soil pH, affecting nutrient availability.
Nutrient Cycling	Disruption	Changes in temperature and moisture affect microbial processes that control nutrient cycling.
Salinity	Increase in coastal areas	Rising sea levels and increased evaporation can lead to saltwater intrusion and soil salinization.
Soil Carbon Storage	Decrease	Higher temperatures and altered moisture conditions can reduce the soil's ability to store carbon.
Soil Fertility	Decline	Loss of organic matter, nutrients, and changes in pH can reduce soil fertility.
Soil Biodiversity	Reduction	Changes in temperature, moisture, and habitat conditions can negatively impact soil organisms and biodiversity.
Water Holding Capacity	Decrease	Loss of organic matter and soil structure degradation can reduce the soil's ability to retain water.
Soil aggregate stability	Decrease	The disruption of soil aggregates by high-intensity rainfall, temperature increase and decreased organic matter content (exacerbate issues such as compaction, runoff, and erosion)

Qian et al. (2011) investigated the connection between climate change trends and soil temperature trends, finding a strong correlation between soil temperature and air temperature trends, and the depth of snow cover over a 30-year period. They observed a notable decrease in snow cover depth corresponding to an increase in air temperature. Soil temperature responds to climate change in a complex manner, being influenced by a combination of changes in air temperature, precipitation, and snow depth (Zhang et al., 2001). The average annual soil temperature has risen by 0.5–1.0°C across all studied soils and at all depths in response to climate change (Reshotkin

& Khudyakov, 2019). Elevated soil temperature accelerates processes such as organic matter decomposition, microbial activity, nutrient release and nitrification rates.

Soil pH and electrical conductivity

Soil pH indicates the acidity or alkalinity of soil and is crucial for soil health, influenced by factors like parent material, weathering, vegetation, and climate (Brinkman & Sombroek, 1996, 1999). While soil pH generally changes slowly in response to climate change drivers like elevated CO_2, temperature, and precipitation patterns, these factors can indirectly impact pH by affecting soil organic matter, nutrient cycling, and water availability (Reth et al., 2005; Anjali & Dhananjaya, 2019). Exceptions include acid sulphate soils in certain regions subject to long dry seasons, where rapid oxidation can temporarily lower pH levels (Brinkman & Sombroek, 1996). Soil pH tends to decrease with increasing elevation due to leaching of basic cations and higher nitrification rates (Smith et al., 2002).

Soil electrical conductivity measures salt concentration, influencing soil physical, chemical, and biological properties, and crop performance. Studies suggest that under various climate change scenarios, EC decreases with rising temperatures and reduced precipitation (Smith et al., 2002). In climatic regions like the Mediterranean, mildly arid, semi-arid, and arid areas, there's a non-linear relationship between soluble salt concentration and rainfall, with regions receiving less than 200 mm of rainfall showing higher soluble salt content (Pariente 2001; Patil & Lamnganbi, 2018).

Soil cation exchange capacity and Soil nutrient pool

Cation exchange capacity (CEC) refers to a soil's ability to retain exchangeable cations, including essential nutrient ions such as K^+, Ca^{2+} and Mg^{2+}. Climate change, particularly elevated temperatures and altered rainfall patterns, has been observed to impact CEC, particularly in soils with lighter textures. In light-textured soils with low active clay content, CEC is primarily influenced by soil organic matter. As temperatures increase, SOM decomposition may accelerate (Davidson & Janssens, 2006), possibly reducing CEC. Furthermore, low CEC in soil can occur due to the leaching of basic cations caused by heavy rainfall (Anjali & Dhananjay, 2019).

Climate change has the potential to alter soil conditions, which can restrict root growth and lead to nutrient stress. Increase in temperature and changes in precipitation patterns can significantly impact soil moisture and temperature, affecting the mobility and availability of nutrients. Climate change also affects nutrient use efficiency by directly influencing root surface area and the rate of ion influx. Plant nutrient acquisition is influenced by factors like root surface area and the proximity of ions to the root surface. Plants acquire nutrients from the soil solution pool, and the transformation between inorganic and organic pools is influenced by soil temperature and moisture dynamics. Factors such as solution concentration of nitrogen and sulfur are strongly affected by these dynamics (Pareek, 2017).

Nutrient cycling, particularly nitrogen, is closely linked to soil organic carbon cycling, meaning that climate change drivers can influence N cycling, as well as potentially affecting sulfur and phosphorus cycles. Increased CO_2 levels can lead to enrichment in the soil C/N ratio, potentially reducing nitrogen mineralization rates (Gill et al., 2002). This reduction can lower the availability of plant-accessible nitrogen in the soil, ultimately impacting plant productivity. However, Pendall et al. (2004) indicate that although elevated CO_2 levels might not significantly affect nitrogen mineralization directly, the warming associated with higher CO_2 could enhance nitrogen mineralization rates, resulting in more nitrogen in the solution phase.

Soil organic matter

Soil organic matterrepresents a crucial element within soil composition, encompassing plant and animal remnants that undergo decomposition cycle, ultimately reintegrating into the soil. Consequently, it functions as both a source and sink of soil carbon. Soil organic matter exerts influence on numerous soil characteristics, enhancing soil quality through various mechanisms. These include increasing water holding capacity of soil, acting as a reservoir for nutrients, reduced compaction, and promoting aeration. Additionally, it fosters structural stability through the formation of aggregates, increases infiltration rates, enhances soil's buffering capacity, and provides a habitat for soil organisms. Soil organic matter is highly vulnerable to climate change. Soil organic carbon serves as the primary and quantifiable constituent of soil organic matter. Soil carbon stock is approximately double that of the atmosphere and three times that of vegetation (Smith et al., 2008). Soil organic carbon level of a specific soil type is dependent upon various factors, such as climatic factors including temperature and moisture regimes, as well as edaphic factors comprising of clay content, parent material type, and cation exchange capacity (Dawson & Smith, 2007). Elevated temperature accelerates the soil organic matter decomposition rate thereby increasing the depletion of stored soil organic carbon, however, they also increase vegetation productivity, ultimately replenishing the soil through litter deposition. The stock of soil carbon primarily hinges on the total carbon input into the soil and the net carbon loss from it. Numerous studies have indicated that warmer climate often boost plant productivity (SOC input) as well as soil respiration (SOC output), with changes in soil organic carbon stock is dependent upon the balance between these inputs and outputs (Smith et al., 2008; Ziegler et al., 2017), nevertheless, soil input is frequently overlooked (Bradford et al., 2016).

Increased precipitation also enhances soil organic carbonstock by enhancing photosynthesis rate in vegetation, particularly in temperate grasslands. Greater rainfall increases soil's vulnerability to water erosion, leaching, and water saturation, consequently diminishing the rate of organic matter decomposition. Conversely, reduced rainfall makes the soil susceptible to wind erosion and salt accumulation, adversely impacting root growth and ultimately diminishing the addition of organic matter to the soil (Anjali &

Dhananjay, 2019).

The rise in atmospheric CO_2 level fosters plant growth and productivity by enhancing photosynthesis, a phenomenon known as the CO_2 fertilization effect, ultimately leading to increment in soil carbon sequestration. However, elevated CO_2 concentration causes increased microbial activity which in turn, accelerates the decomposition of plant tissues, resulting in a decreasing in SOC levels and higher atmospheric CO_2 levels (Carney et al., 2007; Kirkham, 2011). Zhao et al. (2015) utilized a dynamic vegetation model to simulate SOC stocks under future climate change scenarios in Mongolia. Their findings suggest that SOC levels may not be significantly impacted by climate change in the near term; however, in the long term, this effect is expected to become more pronounced, with significant reduction in SOC projected across most eco-geographical regions.

Soil biological activity

Soil microorganisms stand out as primary contributors towards functioning of soil ecosystem. Soil organisms include bacteria, archaea, *actinomycetes*, fungi, protozoa, and nematode species, inhabit soil ecosystems and perform crucial functions in maintaining fertility, soil structure, and aeration. They play a pivotal role in decomposing organic matter, thereby regulating the release of nutrients and facilitating the biogeochemical cycling of soil nutrients. Consequently, these organisms are integral components of the global nitrogen and carbon cycles, exerting influence on greenhouse gas concentrations in the atmosphere (Brevik, 2012). Karmakar et al. (2016) reported that global warming may not directly impact soil organisms, as they often possess a broad temperature spectrum. However, the indirect effects of global warming, such as vegetation migration, can influence soil organisms as it regulates the temperature and rainfall patterns of a given region, indirectly affecting the habitat and conditions for soil organisms. Although the response of soil microbes to elevated CO_2 levels is highly variable due to differences in the distribution of plant carbon across various plant-soil systems (Pareek, 2017), heightened atmospheric CO_2 concentrations generally lead to increased plant growth. This results in a greater influx of carbon into the soil, consequently stimulating microbial growth and activity. Such stimulation significantly impacts nitrogen fixation, immobilization, and denitrification rates (Karmaker et al., 2016; Pareek, 2017). Additionally, elevated CO_2 levels have been observed to increase plant nitrogen uptake, available carbon for microbes, and microbial biomass carbon (MBC). However, they also cause a reduction in available soil nitrogen and microbial respiration per unit of biomass (Hu et al., 2001).

In many cases, symbiotic nitrogen fixation has been observed to increase under elevated CO_2 level, when phosphorus, potassium, and other non-nitrogenous substances are not limiting factors. However, free-living heterotrophic nitrogen fixers have not shown a significant response to elevated CO_2 levels in long-term trials (Reich et al., 2006). Furthermore, increased mycorrhizal colonization has been documented under elevated atmospheric CO_2 conditions. This is attributed to increase in nutrient demand by plants, leading to increased rates of carbon assimilation and subsequent allocation of more photosynthate to roots and mycorrhizal fungi (Pareek, 2017). A common assumption is that elevated CO_2 levels lead to greater soil carbon availability and fungal biomass compared to bacterial biomass. Higher plant productivity under increased CO_2 results in greater quantities of litter, crop residues, and root biomass, thereby increasing the organic matter content in the soil. The addition of this organic matter stimulates the activity of soil macrofauna, including earthworms, which in turn improves infiltration rates and increases the number of stable biopores, facilitating bypass flow (Brinkman & Sombroek, 1996).

Climate change exerts both direct and indirect effects on soil microbial communities, which affects greenhouse gas production and global warming (Fig. 1). Climate change directly influences soil microorganisms and greenhouse gas production by increasing temperatures and causing erratic precipitation patterns, while, indirect effects, such as elevated CO_2 levels, alter plant productivity and diversity, thereby changing the physicochemical conditions of the soil and the carbon supply to the soil. This, in turn, enhances the activity of soil microbes involved in decomposition processes, leading to increased efflux of CO_2 (Bardgett et al., 2008).

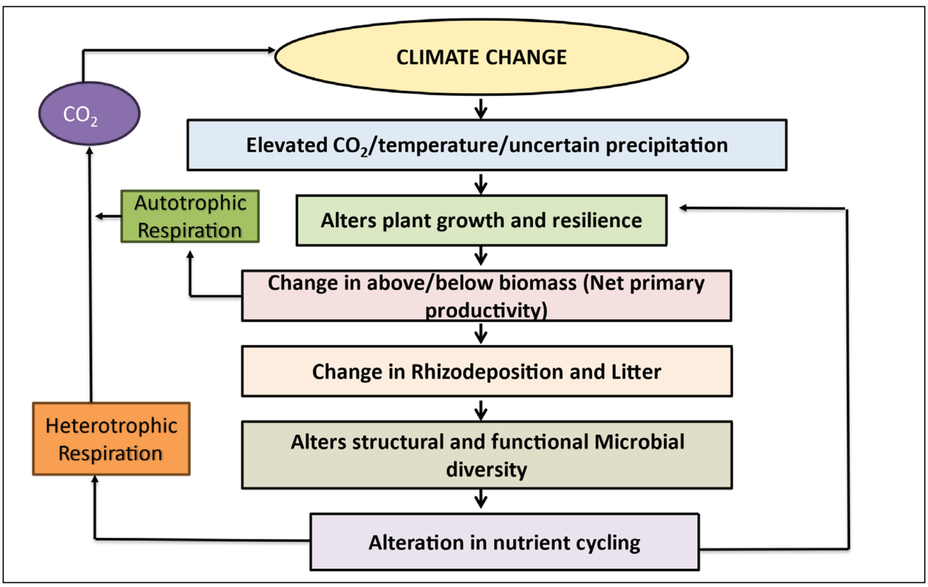

Figure 1: Direct and indirect impact of climate change on soil micro-organisms activity (consequently on nutrient cycling and further plant growth) and routes of feedback through CO_2 production (Redrawn, Source: Bardgett et al. (2008)

Conclusion

Soil stands as the primary determinant of agricultural production and efficiency. Changes in climatic conditions exert significant effects on the physical, chemical, and biological aspects of soil. Drastic shifts in climatic elements result in the degradation of soil organic matter, microbial activity, and nutrient use efficiency thereby diminishing soil fertility. Implementation of climate-smart management techniques not only replenishes soil fertility but also enhances soil carbon sequestration and bolsters resilience against climate change. Despite ample opportunities for greenhouse gases mitigation in agriculture, numerous hurdles must be overcome. The gap between the technical potential and actual implementation of GHG mitigation is due to several barriers, including conflicting climate and non-climate policies, institutional limitations, societal influences, educational gaps, and economic challenges. To tailor technology adoption to local conditions, it's essential to engage local farmers, extension agents, and research institutions. Addressing these challenges requires increased research and development in mitigation and adaptation, capacity-building initiatives, development activities, and changes in land-use management practices.

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