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Impact of Climate Change on Soil Properties and Functions

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Authors Contribution

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Abstract

Climate change is a pressing global concern with far-reaching implications and its impact on soil properties is a critical aspect that warrants comprehensive investigation. This abstract delves into the multifaceted effects of climate change on soil, highlighting the intricate relationships between climate patterns and soil characteristics. Rising temperatures associated with climate change contribute to increased evaporation rates, leading to changes in soil moisture levels. These alterations can influence soil structure, affecting porosity, compaction and water retention capacity. Additionally, shifting precipitation patterns may result in changes to soil erosion and sedimentation rates, impacting nutrient cycling and the overall fertility of the soil. The increase in extreme weather events, such as floods and droughts, intensifies soil erosion and nutrient loss. Changes in temperature and precipitation also influence microbial activity and diversity in the soil, impacting crucial processes like decomposition and nutrient mineralization. These alterations in microbial communities can further cascade into shifts in soil organic matter content and nutrient availability. Furthermore, the interaction between climate change and soil properties extends to the realm of soil carbon sequestration. Altered conditions may affect the balance between carbon inputs and outputs, influencing the capacity of soils to act as carbon sinks. Understanding these complex dynamics is imperative for sustainable land management practices and developing strategies to mitigate the adverse effects of climate change on soil properties. This review paper throws light on the complex interplay between climate change and soil properties underscoring the need for interdisciplinary research to unravel the intricacies of this relationship. Such knowledge is indispensable for formulating effective adaptation and mitigation strategies to safeguard soil health, ensuring the resilience of ecosystems and global food security in the face of ongoing climate challenges.

Keywords : Climate change, Soil health, Carbon sequestration, Soil properties

Climate encompasses long-term atmospheric conditions influenced by factors like latitude, altitude, water bodies, wind and human activities. The escalating population is a key driver of climate change, disrupting the Earth's equilibrium. Scientifically studied terms like 'global warming' and 'climate change' describe the Earth's rising average temperature due to greenhouse gas emissions.

Soil systems are crucial for sustainable development as they serve multiple functions such as producing biomass (food, feed, fibre and fuel), supporting biodiversity and gene pools, purifying water and air, reducing greenhouse gas emissions, sequestering carbon and providing cultural, recreational and human health. Soil formation is shaped by the interplay of climate, biota and parent material, while topography acts as a modifier. Changes in these factors, especially climate, can directly and indirectly impact soils, influencing their evolution, use and management. Climate change consequences encompass rising temperatures and the occurrence of extreme weather events like heavy rainfall, droughts, frosts, storms and coastal sea-level rise. These impacts can heighten the risks posed to the soil, including soil erosion, compaction, decreased fertility and diminished agricultural output, thus undermining both food security and environmental sustainability (Ostle *et al*., 2009).

This paper provides an overview of climate change, its impacts on soil health and strategies that can be implemented to effectively manage the rapidly changing climate in the context of contemporary agriculture.

Impact of Climate Change on the Environment

Climate plays a pivotal role in shaping human-managed ecosystems, affecting agricultural and residential areas, rock and mineral weathering processes, soil development and water availability. It influences the severity of droughts, storms and floods, impacting biomes defined by plant communities. Climate change, coupled with land management, alters net primary productivity by influencing soil processes, encompassing physical, chemical and biological attributes linked to functional soil processes (Dalal *et al*., 2000; Haynes, 2008; Idowu *et al*., 2009; Kinyangi *et al*., 2007 and Reynolds *et al*., 2009). The Intergovernmental Panel on Climate Change (IPCC) in its Sixth Assessment Report, titled 'Climate Change 2021: The Physical Science Basis' has revealed that the planet is irrevocably headed towards warming by 1.5 degrees Celsius over pre-industrial times in the next two decades with global temperature warming by at least 2.7°C by 2100, calling it 'Code red for humanity'.

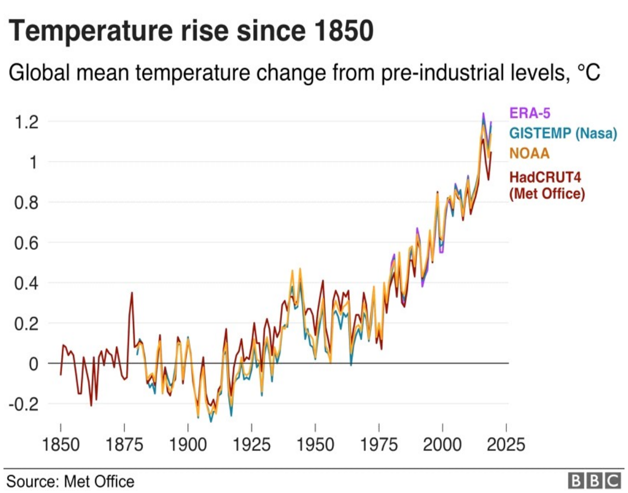

Fig. 1 : Global Mean temperature rise from 1850 till 2025

In 2019, global net anthropogenic Greenhouse gas (GHG) emissions were at 59 Gigatonnes of carbon dioxide equivalent ($GtCO_2$), 54 per cent higher than in 1990 (IPCC, 2023: Climate Change 2023: Synthesis Report).

Impact of Climate Change on Agriculture

Climate change significantly affects global agriculture, particularly in terms of food security. This encompasses food availability, accessibility, utilization and overall food system stability. These impacts have wide-range consequences, affecting human health, natural resources and food production and distribution worldwide (FAO, 2008). Climate change is a major driver of ecological disruption and its effects on the distribution of species can have cascading impacts on ecosystems and biodiversity (EEA, 2019 & EEA, 2020). Climate change poses a threat to agricultural yields, impacting crops differently across countries and types. Assessing regional consequences is complex, considering factors like crop variety, location and elevation. The effects must be distinguished from technological advancements and yearly fluctuations. A debate persists on whether elevated CO_2 levels counteract climate change's adverse effects on photosynthetic activity (Sultan *et al*., 2016).

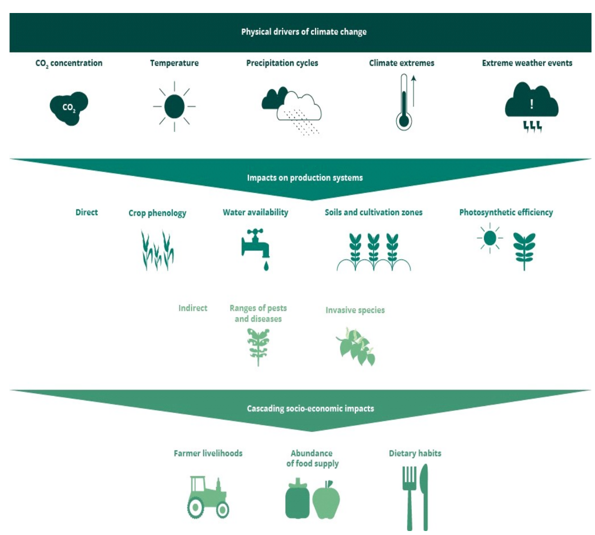

Fig. 2 : Impact of climate change on Agriculture (Arvis *et al*., 2020)

Annual climate variations, depending on the crop and region, contribute significantly, accounting for up to half of the yield variability (Vogel *et al*., 2019). Given that climate change is expected to exacerbate the frequency and severity of extreme weather events (IPCC, 2014), we can anticipate increased volatility in agricultural outcomes. Climate change has shown detrimental impacts on major food crop productivity in Europe and sub-Saharan Africa in recent decades, while Latin America has experienced positive effects, and North America and Asia have witnessed variable outcomes (Ray *et al*., 2019). Climate change poses dire threats to agriculture, disrupting crop yields, water availability and pest patterns, thereby jeopardizing food security. This is particularly concerning for densely populated developing nations like India.

Impact of Climate Change on Soil Properties and Functions

The response of soil to climate change is anticipated to be intricate due to several factors:

1. The intricate network of sequential, simultaneous, and often time-dependent chemical, biological and hydrological reactions and processes.
2. The distribution of chemical elements, nutrients, and contaminants across the solid, liquid and gaseous phases of the soil.
3. The scale-dependent effects stemming from mineralogical, chemical and physical hetero geneities.
4. The interconnected, yet poorly understood, short- and long-term effects on soils induced by climate extremes such as heatwaves and droughts.

To address these and other related issues, research should be carried out at various spatial scales, ranging from the molecular and nano levels to soil particles (µm), soil aggregates (mm), soil horizons (cm), different soil types, soil orders, regional and global scales. Similarly, investigations should encompass a broad range of temporal scales, spanning from minutes to days, days to years, years to decades, decades to centuries, centuries to millennia and even millennia to epochs/eras.

Impact of Climate Change on Soil Formation

In the natural soil formation processes, the concept of pedogenic inertia leads to varying time delays and response rates for different soil types found in different regions across the world (Lal *et al*., 1994 and Rounsevell *et al*., 1994). In Fig. 5 two instances are provided to illustrate the influence of four potential climate scenarios on two significant soil processes: soil texture differentiation within the soil profile and the soil organic matter cycle (Brinkman & Brammer, 1990 and Scharpenseel *et al*., 1990).

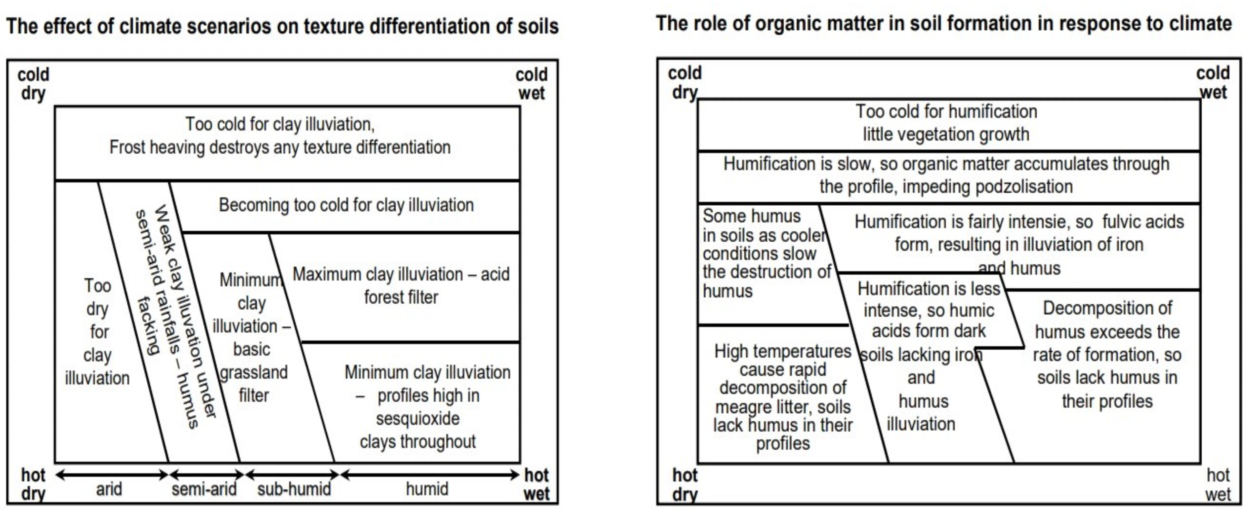

Fig. 3 : Effect of four potential climate scenarios on texture differentiation and organic matter regime (Scharpenseel *et al.*, 1990)

Soil formation factors play a crucial role in shaping distinct soil processes and among the significant climatic elements influencing these pedogenic processes are temperature, precipitation and their fluctuations. (Yaalon, 1983 and Anderson, 1988). Once soil attains a state of 'maturity', its processes stabilize or reach a quasi-equilibrium with the environment. Nevertheless, alterations in environmental factors, such as variations in precipitation levels, can substantially alter the trajectories of soil development, as demonstrated in research on Paleosols (Birkeland, 1999 and Mack, 1991). Climate, a crucial determinant of soil formation, exerts both direct and indirect effects (Hotchkiss *et al*., 2000). Its direct impact encompasses factors like heat, radiation and precipitation influencing the soil environment. (Molnar & England, 1990). Indirect effects stem from climate's influence on the broader biosphere, which subsequently impacts soil properties and formation.

Thus, Temperature and moisture levels intricately regulate mineral compound alterations, influencing weathering pace, accumulation of resultant products, vegetation distribution, dynamics of organic matter, diversity of soil microorganisms and fauna and the mechanisms of water erosion. These interdependent factors underscore the delicate balance in ecosystems, shaping landscapes and impacting ecological processes on various scales.

Impact of Climate Change on Soil Physical Health

Soil Structure and Texture : Soil texture, a slowly changing factor, influences a soil's sensitivity to climate variations. Clay soils, in particular, reveal heightened sensitivity during increased wetting and drying cycles. This induces cracks, accelerating water movement and potentially compromising the soil's filtering capacity. This phenomenon, observed in clay soils, may intensify with prolonged droughts and heavy precipitation events (Rounsevell, 1994). In a study, researchers (Bormann, 2012) assessed how differently soil textures respond to climate change using a physically based Soil-Vegetation-Atmosphere-Transfer model (SVAT) with A_1B and B_1 emission scenarios. They discovered that soils with high water retention (silt soils) were most sensitive to climate changes, while clay soils were less sensitive. Sensitivity was also influenced by factors like groundwater depth, vegetation density, rooting depths, and transpiration. The sensitivity pattern depended on soil texture and was influenced by model boundary conditions (*e.g.,* groundwater level, vegetation), but soil texture predominantly determined how soil responded to regional climate change. Soil texture significantly impacts biomass production and the suitability of vegetation for a particular area. For example, research revealed that finer soil textures may lead to a decrease in grass cover. (Istanbulluoglu & Bras, 2006).

Climate change profoundly affects soil structure, type, spatial distribution and the stability of soil aggregates through intricate processes. Direct impacts involve raindrop erosion, surface runoff, water infiltration and extreme rainfall events. Indirect effects stem from the sensitivity of earthworms, termites and soil micro organisms to climate change. Changes in vegetation patterns and land use practices also contribute to indirect effects (Varallyay, 2010).

Soil aggregate size and stability, as well as porosity and pore size distribution, are crucial factors governing soil moisture, aeration and storage capacity for water (infiltration and retention). Changes in porosity directly influence soil conditions, affecting CO_2 emissions under aerobic conditions and CH_4 emissions under anaerobic conditions (Porporato *et al*., 2004). Intensive rainfall and raindrops play a significant role in aggregate degradation, rising temperatures, coupled with reduced water availability, lower biomass and decreased soil organic matter content, can lead to decreased aggregate size and stability (Lavee *et al*., 1998). Porosity which is strongly linked to soil physical quality, bulk density, micro porosity and functions of the pore volume are affected by decreased microbial activity, reduced root growth and exudates, reduced aggregate stability. The heightened rainfall intensities attributed to climate change results in rain droplets impacting the sodic soils, thereby inducing surface sealing.

This phenomenon adversely affects crop emergence and growth while also elevating the likelihood of surface runoff (Atish & Mutum, 2018).

Unsustainable farming practices like Intensive cultivation without proper soil conservation coupled with climate change, exacerbate adverse effects on soil health and the ecological environment underscoring the need for sustainable agricultural approaches to mitigate these challenges.

Soil Moisture : Soil moisture stress may significantly reduce healthy soil functioning, consequently affecting plant productivity (Mills *et al*., 2014). In a study, it was observed that the shift towards drier and warmer soil conditions can lead to increased evapotranspiration loss of water, an uptick in organic carbon turnover and alterations in precipitation patterns can influence water availability. Furthermore, the authors underscored the adverse and long-term effects of precipitation changes on hydro-physical soil properties, attributing these effects to the accelerated decomposition of organic matter under wet condition (Buytaert *et al*., 2011).

Additionally, land use can play a role in these changes. The overall impact of climate, hydrology, vegetation, and land use changes is seen in the field's water balance and soil moisture patterns (Varallyay, 1990). Evapotranspiration rates seem to rely on temperature, suggesting that the water advantages from elevated atmospheric CO_2 may diminish or disappear in regions experiencing excessive temperature regimes (Ramakrishna, 2017).

Soil Temperature : In Gujarat's Bara tract, rising temperatures, especially in arid conditions, heighten evaporative demand, impacting the agricultural season over the past 30 years. Farmers note increased climate uncertainty with higher winter temperatures, reduced atmospheric moisture for winter crops, irregular rainfall patterns and milder winters affecting wheat grain size. Scientific studies confirm rising winter temperatures, impacting crucial factors like dew, essential for non-irrigated crop growth. Changes in the southwest monsoon further complicate matters, leading to waterlogging and reduced cropping intensity in black cotton soil. These trends, observed over 4-5 years, reflect the complex interplay of climate shifts impacting local agriculture (Anil *et al.*, 2011). Elevated soil temperatures accelerate processes like organic matter decomposition and nutrient release. Surface vegetation changes, influenced by climate change or adaptive management, can further impact soil temperature.

Impact of Climate Change on Soil Chemical Health

Key soil chemical properties include pH, electric conductivity (indicating soluble salt content), nutrient

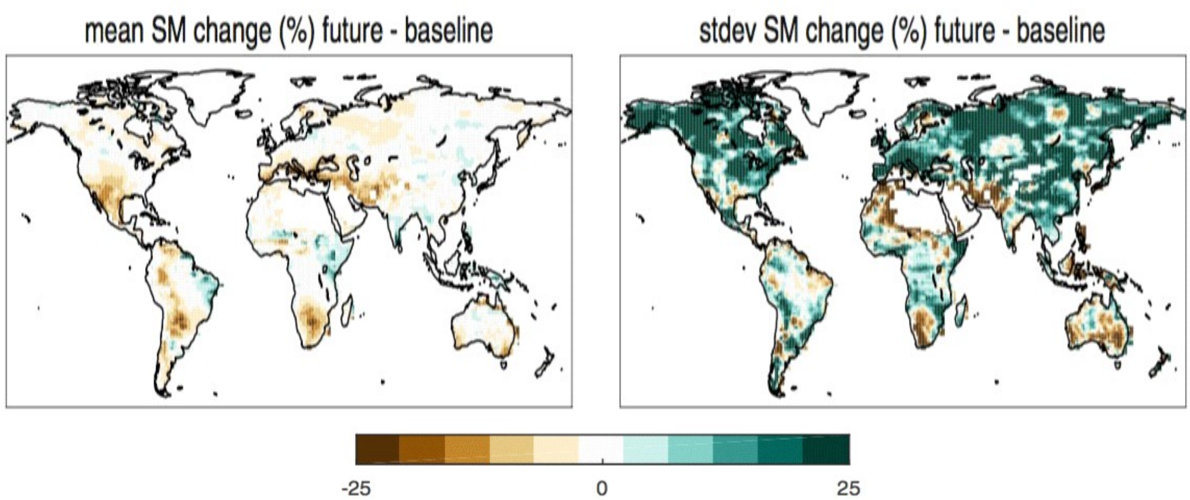

Fig. 4 : Left: The projected percentage change in mean soil moisture between a "baseline period" (1971-2000) and "future period" (2056-2085). Right : The projected percentage change in soil moisture variability between the baseline and future periods. Brown shows percentage decreases while dark green shows percentage increases (Green *et al.*, 2019)

and carbonate distribution in the soil profile, cation exchange capacity (CEC) and base saturation (BS) value and buffering capacity. While soil carbon cycling is essential for understanding chemical responses to climate change, this paper focuses on direct impacts on soil chemical properties due to space limitations.

Soil pH

Soil pH generally remains stable despite direct climate factors like temperature and precipitation changes. However, climate change indirectly affects soil pH through impacts on organic matter, carbon cycles, nutrient cycles, plant-available water and productivity. Increased precipitation intensifies soil acidification by enhancing basic cation leaching, lowering pH, mobilizing potentially toxic elements, and depleting basic cations, especially in well-drained soils with heavy rainfall (Brinkman, 1990). In wetter climates, soil acidification may rise if buffering pools are depleted. Furthermore, changes in rainfall patterns due to daily and seasonal climate variations can affect soil pH. During seasons with low to moderate rainfall, higher salt content forces more exchangeable H^+ ions into the soil solution, reducing pH. Conversely, wet seasons dilute or remove salts from the topsoil, raising soil pH (Rengel, 2002). This seasonal salt content variation differs from long-term effects occurring over decades and centuries, where increased rainfall leads to basic cation leaching and soil acidification.

Cation Exchange Capacity and Buffering Capacity

Cation exchange capacity (CEC) plays a vital role in soil fertility by retaining essential cations like Ca, Mg and K and immobilizing potentially harmful ones like Al and Mn. CEC is linked to soil organic matter, so increased temperatures causing faster organic matter decomposition (Davidson & Janssens, 2006) which can decrease CEC in coarse-textured and low-activity clay soils. Additionally, heavy rainfall can lead to low CEC by leaching basic cations. Soils in recently rejuvenated landscapes have a higher content of primary minerals and may face reduced buffering capacity when exposed to increased rainfall (Vitousek *et al*., 2003 and Chadwick *et al*., 2003).

Acidification, Salinization, Sodicity in Soil

Substantial rainfall increases can result in more leaching, nutrient loss and potential acidification, depending on soil buffering capacity (Atish & Mutum, 2018). Conversely, reduced rainfall decreases the severity and scope of acidification (Dent, 1986). Acid sulphate soils are developed as a result of the oxidation of pyrite-rich parent materials when they are drained. The acidification process may aggravate the mobilization of toxic elements (*e.g.,* heavy metals) resulting in non-congenial conditions for plants and other living organisms.

Thermal expansion could result in a yearly sea level rise of 3 mm due to glacial melting on Earth causing rapid salinization of agricultural lands and groundwater, which is beyond control (Vengosh, 2005). Elevating temperatures and decreasing annual precipitation reduce leaching intensity in soils. This may enhance salinization and carbonate accumulation processes, potentially leading to the formation of salic, gypsic, calcic horizons or hard pans. In areas currently affected by salt where the source is shallow ground water, if a decline in groundwater levels is anticipated, the upward capillary transport will decrease, resulting in reduced transport of soluble salts towards the surface.

Soil Fertility and Productivity : It is projected that distinct soil processes and qualities associated to soil fertility would be impacted differently by the agents of climate changes such as changes in precipitation pattern, increasing temperatures and higher CO_2 levels. The temperature and moisture conditions in the root zone, which are crucial for determining nutrient availability to plants, root growth and development, carbon allocation to roots and the control of nutrient uptake, are greatly influence by changes in air temperatures and precipitation patterns.

Nutrient Availability and Acquisition

According to Jungk (2002), nutrient accessibility to plants hinges on soil chemical properties, ion position relative to roots and the distance nutrients must travel to reach roots. Plant nutrient acquisition involves

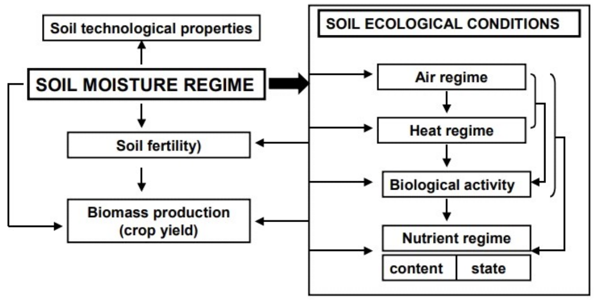

Fig. 5 : The relationships between soil moisture regime, other soil ecological conditions and soil fertility (Cacciotti *et al.*, 2010)

physiological processes controlling nutrient transport to roots, modifying chemical and positional nutrient availability. Given soil moisture, temperature and carbon allocation's pivotal role in nutrient acquisition, changes in these processes are expected to reflect the impacts of a shifting climate.

Drought intensifies nutrient loss vulnerability from the root zone, primarily through erosion (Gupta, 1993). Reduced soil moisture limits water-soluble nutrient diffusion, affecting nitrate, sulphate, calcium, magnesium and silicon, impacting short and long distances (Mackay & Barber, 1985 and Barber, 1995). Roots adapt by extending length and surface area, modifying architecture to capture less mobile nutrients like phosphorus (Lynch & Brown, 2001). Drought hampers root growth and function, diminishing nutrient acquisition capacity (Marschner, 1995). It also impedes nitrogen fixation in legumes, altering soil microbial communities and C and N transformations, affecting soil fertility and nutrient cycling (Gonzalez *et al*., 2001; Ladrera *et al*., 2007 and Schimel, 2007). Poorly drained or intensely rained agricultural areas can lead to waterlogged soils, causing hypoxia and shifting soil redox status. This can induce toxicities of manganese, iron, aluminum, and boron, reducing crop yields. Hypoxia also leads to nutrient deficiencies as oxygen-dependent ATP generation for ion transport into root cells is impaired (Atwell *et al*., 1990). Moreover, under hypoxic conditions, substantial nitrogen losses occur through denitrification as microorganisms use nitrate as an alternative electron acceptor (Prade & Trolldenier, 1990). Soil warming can significantly boost nutrient uptake (100-300%) by expanding root surface area and accelerating nutrient diffusion and water influx rates (Ching & Barbers, 1979). Rising temperatures notably impact nutrient status, especially reducing phosphorus acquisition, through changes in plant phenology (Nord & Lynch, 2009). Elevated temperatures enhance nutrient uptake in the rhizosphere by accelerating ion diffusion rates and increasing root metabolism (Bassirirad, 2000). However, nutrient uptake depends on sufficient soil moisture and in arid conditions, elevated temperatures may reduce acquisition due to mass flow limitations (Cramer *et al*., 2009).

TABLE 1

Potential interactions of global change variables with mineral stress (Clair & Lynch, 2010)

Process	Global change variables	Interaction with mineral stress
Erosion	Heavy precipitation, drought	Loss of soil nutrients, SOC, fertilizer
Transpiration driven mass flow	Drought, temperature, RH, CO_2	NO_3, SO_4, Ca, Mg & Si
Root growth and architecture	Drought, soil temperature, CO_2	All nutrients especially P, K
Mycorrhizhas	CO_2	P, Zn (VAM), N (ectomycorrhiza)
Soil microbes (N cycling)	Drought, soil temperature	N
Biological N fixation	Drought, soil temperature	N
Soil redox status	Flooding	Mn, Fe, Al, B (micronutrients)
Soil leaching	Heavy precipitation	NO_3, SO_4, Ca, Mg
Plant phenology	Temperature	N, P, K
Soil organic carbon status	Soil moisture, soil temperature, CO_2	All nutrients
Salinization	Precipitation, temperature	N, K, Ca, Mg

Nutrient Cycles

The nutrient cycle, especially nitrogen, is crucial for soil fertility, intertwined with carbon and water cycles. Changes in carbon and water cycles impact soil nutrient availability. Carbon and nitrogen cycles are vital in soil-climate interactions, as they constitute essential components of soil organic matter (Brady & Weil, 2008). Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are key long-lived greenhouse gases (Hansen *et al*., 2007). Human activities, like fossil fuel burning and soil tilling, have disrupted the natural balance, causing an annual release of more carbon (C) and nitrogen (N) into the atmosphere than natural systems can absorb (Pierzynski, 2009). The equilibrium between added and emitted soil carbon (C) determines whether total C content rises or falls, influencing atmospheric C levels. Anticipated climate changes, including temperature increases and reduced precipitation, are expected to raise soil pH and decrease electrical conductivity, affecting nitrification potential and ammonium concentration (Smith *et al*., 2002). Higher soil pH triggers ammonia volatilization, potentially causing soil acidification and eutrophication issues. Climate-induced temperature rises could exacerbate ammonia volatilization, intensifying nitrogen pollution (Vander *et al*., 2007). Organic farming systems generally exhibit lower N_2O emissions than conventional systems, although tilled soils may show variable results (Grandy *et al*., 2006). Nitrous oxide (N_2O) levels rise due to increased microbial activity in expanding agricultural areas using fertilizers and manure amendments, contributing to higher N_2O production with increased nitrogen fertilizer use and denitrification rates (Grant *et al*., 2006). Methane plays a crucial role in the soil carbon cycle, with agriculture contributing 47 per cent of annual anthropogenic methane emissions. Rice cultivation is a major source. The type of vegetation influences methane emissions; forest soils act as sinks, maize fields have neutral balances and grass-covered areas emit methane. Soil properties, influenced by dominant vegetation, impact methane-consuming microbe survival. Agricultural practices, such as dryland tillage or reducing soil saturation during rice cultivation, can mitigate methane production. Fertilizer types also affect emissions; mineral-based potassium shows no effect, while phosphorus fertilizers can decrease methane emissions due to increased root exudates (Heilig, 1994; Hu *et al*., 2001; Wassmann *et al*., 1993 and Lu *et al*., 1999).

Impact of Climate Change on Soil Biological Health

The soil system's chemistry and physics create the backdrop, but it's the soil biota that demonstrates adaptability to shifts in environmental conditions. (Kibblewhite *et al*., 2008)

Soil Organic Matter

Soil organic matter (SOM) plays a vital role in determining soil fertility, influencing key soil functions like cation exchange and water retention, and exerting significant control over soil pH. Additionally, SOM enhances soil aggregation, augments water retention available to plants and ultimately, a decline in SOM can diminish soil fertility and biodiversity while adversely affecting soil structure. The impact of global warming on the storage of soil organic carbon is significant, as research has shown a decrease in SOC storage correlating with the increase in mean annual temperature (MAT) ($r = -0.735$, $p < 0.001$) (Tan *et al*. 2020). In general, the decomposition of organic matter in soil speeds up as temperatures increase. Consequently, an increase in temperature, along with enhanced plant productivity and its subsequent contribution to soil, as well as increased precipitation that can promote CO_2 fertilization and atmospheric nitrogen deposition, can collectively enhance soil organic matter content. Climate-induced changes in soil moisture content can significantly impact the decomposition of soil organic matter, often more so than temperature increase. In the unsaturated zone, characterized by oxic conditions and efficient aerobic processes, organic matter decomposition accelerates (Golovchenko *et al*., 2007) The highest microbial activity and SOM decomposition rates occur when soil moisture content is around 50-60 per cent. Arid or semiarid ecosystems experience SOM

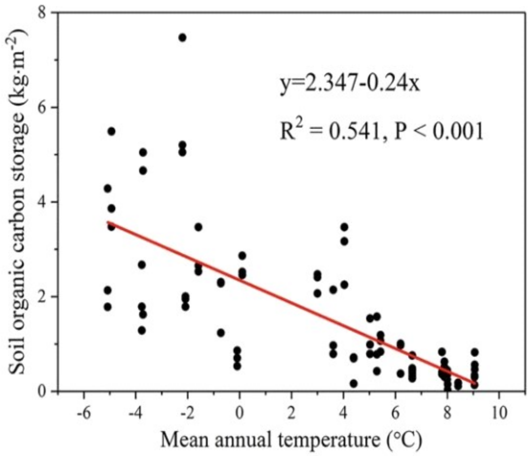

Fig. 6 : Relationship between SOC storage and mean annual temperature (MAT) (Tan *et al*. 2020)

decomposition due to low soil moisture availability. However, in other ecosystems, excessive soil moisture can impede the decomposition process (Plante *et al*., 2014).

Human activities have a significant impact on the carbon balance in cultivated soils. Soil management practices like no-till systems can lead to reduced CO_2 emissions from the soil and increased carbon sequestration, in contrast to intensive tillage-based management systems (Fig. 7) (Hobbs *et al*., 2010).

Soil Microbial Biomass and Soil Respiration

Studies show that short-term environmental shifts affect soil microbial biomass (Pregitzer *et al.*, 2008), with long-term climatic warming experiments indicating a notable reduction (Rinnan *et al*., 2007). Elevated temperatures can enhance microbial activity and abundance, promoting nutrient cycling in temperate ecosystems if water and nutrients are sufficient (Vinolas *et al*., 2001 and Castro *et al*., 2010). However, prolonged elevated carbon dioxide levels are not expected to significantly impact microbial biomass carbon and community structure (Niklaus *et al*., 2003). Fungi, with a higher C/N ratio, require less nitrogen than bacteria. In nitrogen-reduced soil conditions with elevated CO_2, there may be an increase in the fungal population (Hu *et al*., 2001). The study revealed that precipitation treatment significantly influenced bacterial phyla abundance, particularly Proteobacteria and Acidobacteria, but carbon dioxide and temperature had no significant impact. Wet conditions favoured Proteobacteria, while dry conditions promoted Acidobacteria, aligning with their metabolic preferences (Castro *et al*., 2009). Soil respiration is notably sensitive to variations in the seasonal timing of rainfall and soil moisture,

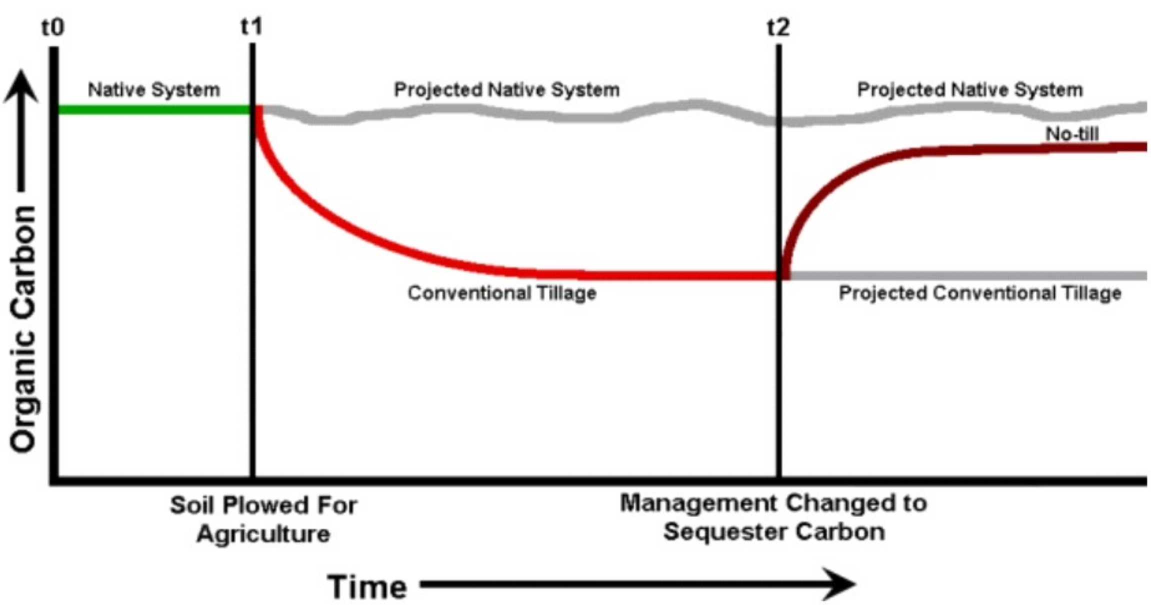

Fig. 7 : Tilling a native soil leads to reduced soil organic C levels, while management changes such as a conversion to no-till techniques may lead to increased soil organic C as compared to conventional tillage techniques (Hobbs *et al*., 2010)

a phenomenon anticipated to shift in accordance with global and regional climate models.

Enzyme Activity

Soil enzyme activities show rapid response to changes in soil management. Studies on individual enzyme activities reveal significant temporal and spatial variability, frequently resulting in conflicting outcomes (Ruiz *et al*., 2009). It was demonstrated that elevated CO_2 can boost microbial enzyme activities by modifying the quantity and quality of below-ground carbon input from plants (Dorodniko *et al*., 2009).

However, there are still much to uncover about the role of soil microbial enzyme activities in organic carbon turnover, nutrient cycling, and greenhouse gas emissions.

Nutrient Transformation

Global climate change-induced alterations in moisture and temperature significantly impact soil's biological transformations. Higher temperatures can spur microbial activity, potentially accelerating the liberation of bioavailable nitrogen (N) and phosphorus (P) from organic matter. This process contributes to nutrient cycling and influences ecosystem productivity and dynamics (Weintraub & Schimel, 2005). Soil warming may raise inorganic N and P pools by accelerating processes like ammonification, nitrification and P mineralization (Schimel *et al*., 2004 and Natali *et al*., 2011). Changes in precipitation patterns can lower the water table, increasing the unsaturated zone's depth, providing more oxygen to drier soils and enhancing plant nutrient availability through organic matter oxidation (Macrae *et al*., 2013).

Influence of Climate Climate Change on Soil Degradation : Climate change affects soil processes, leading to varying impacts-some beneficial, others harmful or catastrophic. Annual global losses from land degradation and desertification range from US$ 6.3 to 10.6 trillion, indicating a significant issue. The decline in soil organic carbon is a crucial indicator of land degradation, posing challenges to sustainable development, biodiversity and climate change efforts. Despite substantial costs, accurately measuring the indirect consequences of land degradation remains complex.

Climate change significantly impacts soil properties, posing challenges to agriculture and the environment. Rising temperatures, altered precipitation and extreme weather events disrupt soil health, threatening food security, water resources and biodiversity. Prompt action is essential. Mitigation involves reducing greenhouse gas emissions to prevent soil degradation. Adaptation strategies includes focusing on enhancing soil resilience through sustainable land management, afforestation, reforestation and improved water management. Governments, communities and individuals must prioritize soil conservation and adopt science-based practices for a sustainable and resilient future.

According to Pooja *et al*. (2022) farmers must be educated about the benefits of diversified farming and encouraged to adopt modern practices. Creating awareness to farming communities about suitable crop planning, engaging in allied activities like livestock and fisheries, and implementing water-saving technologies and devices which can specifically

TABLE 2

Relation between enzyme activities and elevated CO_2 concentration (Anjali and Dhananjaya, 2019)

Enzyme	Ambient CO_2 (μmol kg^{-1} ha^{-1})	Elevated CO^2 (μmol kg^{-1} ha^{-1})
α1-4 glucosidase	1.0±0.9	2.1± 0.8
β 1,4 glucosidase	145.7±18.6	129.5 ± 7.8
Alk phosphatase	332.4±6.3	234.8± 7.6
N acetyl glucosaminidase	48.0± 2.1	6.7

Soil degradation processes	Soil	Climatic scenarias				Causative factors	
		Cold and Dry	Cold and Wet	Hot and Dry	Hot and Wet	Natural	Antrop
Soil erosion by water	E	4	1	4	1	1,2,3	9,10,11,12
Soil erosion by wind	D	3	4	2	4	3	9,10,11,12
Acidification	A	3	1	4	1	2,4	13,15
Salinization/Alkalization	S	2	4	1	4	5,6,8	14
Physical degradation	P	3	2	2	1	-	10,12
Extreme moisture regime (water logging)	M	4	1	4	2	5,6,7	11,12,14
Biological degradation	B	3	2	2	1	-	11,16
Unfavourable nutrient regime	N	3	2	2	1	(2,6)	13
Soil pollution (toxicity)	T	4	3	3	4	-	16

1 Strong 2 Medium 3 Slight 4 No or negligible

CAUSATIVE FACTORS:

Natural

1. Undulating surfaces
2. Parent rock
3. Lack of permanent and dense vegetation
4. Litter decomposition
5. Low-lying lands
6. Improper drainage
7. High water table (non saline)
8. High water table (saline)

Antropogeneous

9. Deforestation
10. Overgrazing
11. Irrational land use
12. Improper tillage practices
13. Irrational fertilizer application
14. Improper irrigation
15. Acid deposition
16. Chemical soil pollution

Fig. 8 : The influence of four main climatic scenarios on the main soil degradation processes and their natural and anthropogenic causative factors (Varallyay, 1990 and Szabolcs, 1990).

enhance crop productivity and income. This holistic approach ensures livelihood security for farmers in command areas, promoting sustainable agriculture.

This effort not only protects soils but also gives significant contribution to global climate change mitigation and long-term environmental sustainability.

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