

5. Influence of Climate Change on Soil Processes and Agricultural Productivity

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1. Introduction

Climate change refers to long-term shifts in temperature and weather patterns at global and regional scales. While such changes can occur naturally through variations in solar activity or significant volcanic eruptions, the accelerated warming observed since the nineteenth century is primarily the result of human activities, particularly the extensive use of fossil fuels such as coal, oil and natural gas. In this context, the Intergovernmental Panel on Climate Change (IPCC) and the UNFCCC define climate change as "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods."

The combustion of fossil fuels releases greenhouse gases, primarily carbon dioxide (CO₂) and methane (CH₄), that act as an insulating layer, trapping heat and driving a gradual increase in Earth's surface temperature. These emissions, arising from the energy, industrial, and agricultural sectors, are increasingly expressed through altered precipitation regimes and a greater

frequency of extreme weather events. Central to these interactions is soil, a dynamic and living system that underpins agricultural production. Climatic variations directly affect key soil processes, including organic matter decomposition, nutrient cycling and structural dynamics. Given that soil health underpins sustainable agriculture, disturbances to these processes directly threaten crop productivity and food security. This article elucidates the linkages between major climate drivers and soil-plant systems, providing a rationale for integrated management strategies essential to long-term agricultural sustainability.

1. Climate Change Variables Relevant to Soil and Agriculture

The stability of global agriculture is fundamentally linked to the predictable behaviour of local and regional climates. However, anthropogenic climate change has introduced a period of unprecedented volatility, altering the delicate equilibrium between soil health and crop productivity. By shifting the baselines for temperature, moisture, and atmospheric chemistry, these climatic drivers do not merely impact the plants themselves but fundamentally transform the soil ecosystem that supports

them. The following sections detail the specific variables, ranging from thermal shifts to erratic hydrological cycles, that currently redefine the physical and biological boundaries of modern farming.

2.1. Rising Air and Soil Temperature

- a. **Global and regional warming trends:** Since the pre-industrial era, global mean temperatures have risen by approximately 1.1 °C, though land surfaces have warmed faster, averaging a 1.7 °C increase. Regionally, warming is not uniform; high-latitude regions like the Arctic and the Qinghai-Tibet Plateau are experiencing 'Arctic amplification', where soil warming rates are significantly higher than the global average. These trends lead to a northward shift in arable land but also threaten traditional "breadbasket" regions with heat stress that exceeds the physiological thresholds of staple crops.
- b. **Soil thermal regimes:** Soil temperature is a critical regulator of biogeochemical cycles. Rising temperatures shift the soil thermal regime, accelerating the decomposition of soil organic matter (SOM) and increasing nutrient mineralisation rates. While this may temporarily boost nutrient availability, it often leads to a long-term decline in soil carbon stocks and the release of greenhouse gases like CO₂ and CH₄, creating a positive feedback loop that further intensifies warming.
- c. **Diurnal and seasonal soil temperature shifts:** Climate change is causing a narrowing of the

Diurnal Temperature Range (DTR), as night-time minimum temperatures are rising faster than daytime maximums. This shift affects the structure and physiological functions of the soil microbial community, including respiration. Seasonally, earlier spring warming can trigger premature seed germination or disrupt the synchronisation between crop flowering and the presence of essential pollinators.

2.2. Changes in Precipitation Patterns

- a. **Erratic rainfall:** The hydrological cycle is intensifying, leading to higher variability in the timing and distribution of rain. In many regions, the traditional monsoon seasons are becoming less predictable, with long dry spells followed by intense, short-duration downpours. This unpredictability complicates planting schedules and increases the risk of crop failure in rain-fed agricultural systems, which support a large portion of the global population.
- b. **Drought frequency and intensity:** Rising temperatures increase evapotranspiration rates, depleting soil moisture and groundwater reserves. Drought is often characterised as a "slow-motion disaster" that leads to soil crusting, reduced microbial activity and increased salinity in the root zone. Chronic water stress impairs photosynthesis and nutrient uptake, resulting in significant yield losses in major cereal crops such as wheat and maize.

- c. **Flooding and waterlogging events:** Conversely, the increase in extreme precipitation leads to more frequent flooding and soil waterlogging. When soil pores are saturated with water, oxygen diffusion is severely restricted, creating anaerobic (hypoxic) conditions. This inhibits root respiration and promotes the growth of denitrifiers and methanogens, leading to nitrogen loss through denitrification and increased methane emissions, a potent greenhouse gas.

2.3. Elevated Atmospheric CO₂ Concentration

- a. **CO₂ fertilisation effect: Higher concentrations of atmospheric CO₂ act as a ‘fertiliser’** for C3 plants (such as wheat, rice and soybeans), increasing their rate of photosynthesis and potentially boosting biomass production. However, these yield gains are often offset by a dilution effect, in which increased carbohydrate production reduces the concentration of essential minerals such as zinc, iron, and protein, potentially worsening global hidden hunger.
- b. **Interaction with soil-plant systems:** Elevated CO₂ influences the soil-plant-water nexus by reducing stomatal conductance, which improves the water-use efficiency (WUE) of plants. While this can help crops survive dry spells, the resulting change in the Carbon-to-Nitrogen (C: N) ratio of plant litter can slow soil

decomposition rates. This alters the quality of organic matter entering the soil and shifts the balance of the soil microbial ecosystem toward slower-growing, more resource-efficient species.

2.4. Extreme Climatic Events

Heat waves: Beyond steady warming, discrete heat waves cause acute damage by inducing pollen sterility and flashing moisture out of the soil. When temperatures exceed critical thresholds during sensitive growth stages, such as flowering or grain filling, entire harvests can be lost in a matter of days. Furthermore, heat waves often coincide with droughts, further compounding stress on the soil-plant system.

Cyclones, storms and hail: Intense tropical cyclones and storms cause physical destruction of crops and infrastructure, but their impact on soil is equally devastating. High-velocity winds and torrential rains lead to massive topsoil erosion and nutrient leaching. In coastal agricultural zones, storm surges can cause saltwater intrusion, rendering fertile soils unproductive for years due to high salinity levels.

Freeze-thaw cycles in temperate regions: In temperate and permafrost regions, climate change is altering the frequency and depth of freeze-thaw cycles. Increased fluctuations between freezing and thawing can physically disrupt soil structure, causing ‘frost heaving’ that damages plant roots and increases soil compaction. These cycles trigger short-term increases in nutrient mineralization and nitrous oxide emissions, resulting in greater nitrogen losses and a less efficient

soil nitrogen cycle during the winter and early spring months.

Table 1: Effects of major climate variables on soil processes and their direct consequences for agricultural productivity

Climate Variables	Primary Soil Impacts	Direct Agricultural Consequences
Rising Temperature	Accelerates SOM decomposition, 16–20% reduction in microbial richness, altered nutrient mineralization.	Heat stress during flowering, reduced grain-filling period, higher plant respiration rates at night.
Erratic Precipitation	Flooding: Anaerobic conditions and denitrification. Drought: Increased soil salinity and moisture depletion.	Yield instability, root hypoxia from waterlogging, severe water stress in rain-fed systems.
Elevated CO₂	Shifts in soil C:N ratios, changes in microbial community structure favoring resource-efficient species.	CO ₂ fertilization increases C ₃ crop biomass but causes nutrient dilution (lower protein and minerals).
Extreme Events	Massive topsoil erosion from storms, destruction of soil structure, coastal saltwater intrusion.	Acute physical crop destruction, loss of arable land, increased pest and pathogen pressure.

Freeze–Thaw Cycles	Physical disruption of soil aggregates (frost heaving), nutrient leaching into groundwater.	Damage to overwintering crops, disrupted synchrony between crops and pollinators.
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2. Influence of Climate Change on Soil Physical Processes

The physical integrity of soil is the structural foundation upon which all agricultural productivity is built. As climatic patterns shift toward more extreme oscillations, the mechanical and hydraulic properties of the soil profile are undergoing significant degradation. As a result of these climate-driven physical changes, the essential functions of the soil ecosystem are disrupted.

3.1. Soil Structure and Aggregation

The structural stability of soil is increasingly compromised by the heightened kinetic energy of extreme precipitation events. When high-intensity rainfall strikes the earth, it acts as a mechanical force that shatters soil aggregates through a process known as slaking, where the rapid entry of water causes internal air pressure to burst the bonds holding soil particles together. This primarily results in the loss of macro-aggregates, the larger structural units essential for aeration and drainage, thereby exposing previously protected organic carbon to rapid microbial oxidation. As these aggregates disintegrate, the resulting fine silt and clay particles settle into a dense, impermeable layer at the surface. This surface crusting not only inhibits the emergence of delicate seedlings

but also creates a physical seal that restricts gas exchange and significantly increases the rate of surface runoff, even during moderate rain events.

3.2. Soil Moisture Dynamics

Climate change is fundamentally altering the movement and storage of water within the soil profile, often creating a paradox where fields suffer from moisture stress despite high total rainfall. The formation of surface crusts and the loss of macropores lead to reduced infiltration rates, meaning water is frequently rejected by the soil and lost to runoff rather than recharging the root zone. Simultaneously, rising global temperatures and higher Vapor Pressure Deficits (VPD) accelerate evaporation losses from the upper soil layers, stripping moisture away before crops can utilize it. This evaporative pull is most severe in arid and semi-arid regions, where the top 10–20cm of soil can reach permanent wilting point thresholds much faster than in previous decades. This is further worsened by the decline in soil organic matter, which reduces the soil's overall water retention capacity. Current modeling suggests that for every 1% loss in soil organic matter, a field may lose the ability to store over 20,000 gallons of water per acre, making crops significantly more vulnerable to even short-term dry spells.

3.3. Soil Erosion Processes

Erosion is perhaps the most visible physical consequence of climate change. The Erosivity Factor (or R-factor) of rainfall is increasing; current 2026 studies indicate that the ratio of erosion increase to annual rainfall increase is approximately 1.7. This means a 10% increase in rainfall can lead to a nearly 17% increase in soil loss, as heavy storms strip away the nutrient-rich A-horizon and detach particles and transport them through rills and gullies. Conversely, during the prolonged dry spells and heatwaves that characterize modern climate shifts, the soil loses its cohesive moisture and vegetative protection, becoming highly susceptible to wind erosion. This aeolian transport (wind erosion) specifically targets the clay and organic particles that hold the majority of the soil's fertility, leaving behind coarse, unproductive sands. This cumulative loss of topsoil represents a permanent depletion of productive capacity, as the rate of soil loss now exceeds the rate of pedogenesis (soil formation) by several orders of magnitude in many global regions.

3.4. Soil Texture and Bulk Density Changes

While a soil's basic texture, ratio of sand, silt and clay, remains relatively stable, its bulk density and porosity are highly sensitive to climatic fluctuations and human intervention. Erratic rainfall patterns often narrow the workability window, forcing

farmers to operate heavy machinery on soils that are too wet, which leads to severe subsoil compaction. This increase in bulk density physically restricts root elongation and destroys the network of pores necessary for soil health. The resulting reduction in porosity leads to poor aeration and soil suffocation, where oxygen levels drop low enough to trigger anaerobic conditions. These conditions not only stunt crop growth but also promote the loss of nitrogen through denitrification and increase the production of toxic compounds like ethylene within the soil air spaces, further depressing yields.

3. Influence on Soil Chemical Processes

Chemical soil processes govern the availability of nutrients and the storage of carbon, both of which are being destabilized by shifting climatic baselines. These chemical shifts often occur invisibly but have profound implications for long-term soil fertility.

4.1. Soil Organic Carbon (SOC) Dynamics

Soil Organic Carbon (SOC) is highly sensitive to thermal shifts, as rising temperatures accelerate the metabolic rate of decomposer organisms, leading to the rapid breakdown of organic matter. This increased decomposition rate often outpaces the input of fresh plant litter, significantly reducing the soil's carbon sequestration

potential. This creates a dangerous SOC-climate feedback mechanism as soils lose carbon, they release CO₂ back into the atmosphere, further intensifying global warming and leading to a self-reinforcing cycle of degradation that strips the soil of its natural resilience and water-holding capacity.

4.2. Nutrient Cycling and Availability

Climate change disrupts the synchronized timing of nutrient release and plant demand. Rising temperatures speed up nitrogen mineralization, but if this occurs outside the growing season, it leads to significant nitrate leaching or gaseous loss. Furthermore, changes in soil moisture directly affect phosphorus solubility, while excessive moisture can increase P-availability through reduction, it also increases the risk of runoff. Meanwhile, intensified rainfall events are increasingly responsible for potassium leaching, particularly in coarse-textured soils, leaving crops deficient in the essential elements required for stress tolerance and enzyme activation.

4.3. Soil pH and Salinity

The chemical balance of soil is shifting toward extremes of acidity and salinity. In humid regions, increased precipitation leads to the leaching of basic cations (such as Ca²⁺ and Mg²⁺) and accelerated nitrification, both of which drive soil acidification. Conversely, in

arid and semi-arid regions, high evaporation rates cause minerals to move upward through pores, resulting in a rapid salinity build-up in the root zone. When coupled with poor drainage or the use of marginal irrigation water, these areas face rising sodicity issues, which destroy soil structure and create toxic environments for most staple crops.

4.4 Greenhouse Gas Emissions from Soils

Agricultural soils act as both significant sources and potential sinks for greenhouse gases, with their emission profiles dictated by temperature and moisture. Warmer, aerobic soils primarily emit CO₂, but as flooding and waterlogging become more frequent, anaerobic conditions trigger the production of CH₄ (methane) and N₂O (nitrous oxide). N₂O, in particular, is a potent greenhouse gas with a warming potential nearly 300 times that of CO₂ and its release is being accelerated by the interaction of heavy nitrogen fertilization and erratic, intense rainfall events.

4. Influence on Soil Biological Processes

The biological component of soil, the living fraction, is perhaps the most climate-sensitive. Changes in the subterranean microbiome and fauna can alter the entire trajectory of a growing season.

5.1. Soil Microbial Communities

Soil microbial communities are undergoing rapid shifts in diversity and

function as they struggle to adapt to more frequent heat and moisture stress. Warming tends to favor faster-growing, less efficient microbial species, which can lead to a net loss in microbial biomass carbon and nitrogen. These shifts are not merely numerical, they represent a fundamental change in ‘who does what’ in the soil, often resulting in the loss of specialized microbes that are responsible for suppressing soil-borne pathogens or fixing atmospheric nitrogen.

5.2. Soil Enzyme Activities

The biochemical machinery of the soil, its enzymes, is being recalibrated by climate change. Crucial enzymatic reactions involving dehydrogenase (an indicator of overall microbial activity), urease (nitrogen cycling) and phosphatase (phosphorus mobilization) are highly temperature-dependent. While moderate warming may initially increase these activities, extreme heat can denature these proteins or alter their substrate affinity. This creates a mismatch in nutrient transformation rates, often leaving plants unable to access nutrients during critical reproductive stages.

5.3. Soil Fauna and Biodiversity

Larger soil organisms or ‘ecosystem engineers’, like earthworms, nematodes and arthropods, are highly vulnerable to the physical extremes of climate change. Prolonged droughts can force earthworms into deep-soil

dormancy or cause mass mortality, while flooding events can drown surface-dwelling beneficial insects. Because these fauna are responsible for the initial fragmentation of organic matter and the creation of soil macropores, their decline leads to slower nutrient turnover and a collapse in the soil's natural ability to maintain its own structure and porosity.

5.4. Rhizosphere Processes

The rhizosphere, the narrow zone of soil surrounding plant roots, is a hub of intense biological activity that is currently under climate-driven stress. Changes in atmospheric CO₂ alter root exudation patterns, essentially changing the signals plants send to soil microbes. While some plants may increase exudates to recruit beneficial bacteria during drought, mycorrhizal associations (fungal-root symbioses) can be disrupted by soil temperature spikes. This destabilization of the root-microbe interface reduces the plant's ability to scavenge for water and phosphorus, undermining the very partnerships that help crops survive environmental volatility.

5. Impact on Agricultural Productivity

The transition from soil degradation to tangible economic loss is most evident in the decline of agricultural productivity. Till date, the convergence of physical, chemical and biological soil stressors has created a global challenge where traditional farming wisdom no

longer guarantees a successful harvest. On a global scale, climate change is widening the productivity gap between developed and developing nations. Globally, the yield plateau phenomenon is becoming more common, despite better seeds and more fertilizer, yields of wheat and maize are stagnating because the degraded soil can no longer support the plant's physiological needs under high-heat stress. Current 2026 projections indicate that for every 1°C rise in mean seasonal temperature, wheat yields could decline by 6 to 10% due to shortened grain-filling periods and heat-induced soil moisture deficits. In India, the agricultural sector is uniquely vulnerable due to its heavy reliance on the monsoon and a high percentage of smallholder farmers. Recent data indicates that the Indo-Gangetic Plain, the country's primary food bowl, is facing a severe soil fatigue crisis. Rising temperatures are accelerating the depletion of Soil Organic Carbon (SOC) in Punjab and Haryana, where levels have dropped below 0.5%, making crops highly sensitive to the increasingly frequent heat waves during the wheat-filling stage. Furthermore, the erratic monsoon has led to severe soil erosion in the Deccan Plateau and saltwater intrusion in

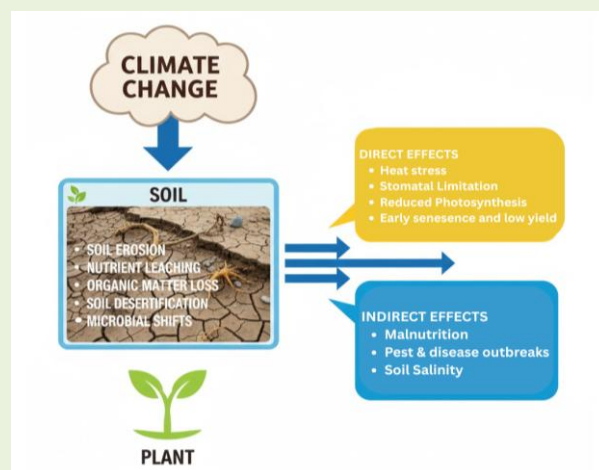
the fertile deltas of West Bengal and Andhra Pradesh, directly threatening the livelihoods of millions.

A critical, often overlooked impact is the decline in food nutritional quality. As CO₂ levels rise, crops like rice and wheat, staples for over 80% of India's population, are exhibiting a dilution effect. While the plants may grow larger, they contain significantly lower concentrations of protein, zinc and iron. In the Indian context, where anemia and micronutrient deficiencies are already prevalent, this decline in crop quality worsens the public health challenge of hidden hunger, where people may consume enough calories but remain malnourished because the soil can no longer provide essential minerals to the plants. The convergence of soil degradation and increasing climate volatility extends beyond environmental and health concerns, giving rise to far-reaching socio-economic consequences. For the farmers, the cost of production is rising as more chemical fertilizers are required to compensate for lost natural soil fertility. This creates a debt trap, when extreme weather events such as the unseasonal hailstorms or prolonged droughts, wipe out harvests. Nationally, this leads to food price inflation and market instability. Global food security now rests on a brittle system where a single season of failed soil-water management in a major exporting country can trigger

a worldwide spike in hunger and poverty.

Effect of Climate change on soil and plants

6. Strategies for Enhancing Soil Resilience and



Agricultural Adaptation

To counter the degradation of soil processes, a transition from conventional intensive farming to Climate-Smart Agriculture (CSA) and Regenerative Practices is essential. These strategies aim to rebuild soil health and create a buffer against climatic shocks.

7.1. Soil-Based Mitigation and Carbon Sequestration

One of the most effective ways to mitigate climate change is to turn agricultural soils back into carbon sinks. Practices such as Conservation Tillage (zero or reduced till) and the application of Biochar can significantly increase Soil Organic Carbon (SOC) levels. By minimizing soil disturbance, farmers can preserve the delicate fungal networks and macro-aggregates that store carbon.

7.2. Integrated Nutrient and Water Management

To address nutrient leaching caused by erratic rainfall, precision agriculture is becoming a necessity. Site-Specific Nutrient Management (SSNM) uses sensors and satellite data to apply fertilizers only when and where the plant needs them, reducing the risk of nitrogen leaching and N₂O emissions. Similarly, to combat water scarcity and salinity, Drip Irrigation and Laser Land Leveling are critical. These technologies ensure that water is delivered directly to the root zone, preventing the upward wicking of salts and maintaining optimal soil moisture dynamics even during heatwaves.

7.3. Diversification and Genetic Adaptation

Relying on a single crop (monoculture) increases the risk of total failure. Crop diversification, such as integrating legumes or millets, which are naturally more drought-tolerant and nitrogen-fixing, can restore soil fertility and provide economic security. Furthermore, breeding climate-resilient crop varieties that are tolerant to salinity, submergence (flood-tolerant) and heat stress is vital. For example, India has successfully introduced *Swarna Sub1* rice variety that can survive underwater for two weeks, protecting yields in flood-prone regions like Bihar and Odisha.

8. Conclusion

The influence of climate change on soil processes represents one of the most significant threats to the stability of the 21st-century food system. As we have explored, the relationship is not linear; rather, it is a complex web of physical, chemical and biological feedbacks. Rising temperatures and erratic precipitation do not just "stress" the plant; they fundamentally dismantle the soil architecture, deplete the carbon stocks and silence the microbial life that makes agriculture possible. In both a global and Indian context, the era of stable agriculture has ended. The thinning of topsoil, the dilution of crop nutrients and the increasing frequency of extreme weather events have made our food systems increasingly brittle. However, the soil also holds the key to our resilience. By shifting our focus from 'exploiting' the soil to 'regenerating' it, we can sequester atmospheric carbon, restore hydrological cycles and ensure that our agricultural lands remain productive for future generations. The path forward requires a global commitment to soil-centric policies that recognize healthy earth as the ultimate foundation of human health and economic security.

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