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REVIEW ARTICLE

Soil temperature dynamics and their implications for soil health and crop productivity: A critical review

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Abstract

Soil temperature is a pivotal factor regulating physical, chemical and biological processes within terrestrial ecosystems, particularly in the rhizosphere where plant–soil interactions are most active. Fluctuations in soil temperature influence texture, structure, aeration and moisture retention, thereby altering nutrient mobility and availability. Temperature also affects key soil chemical properties such as pH, cation exchange capacity and the cycling of essential elements like carbon, nitrogen, phosphorus and potassium. Equally, microbial activity, which is central to decomposition, enzymatic reactions and nutrient mineralization is highly temperature-sensitive, with implications for soil fertility and ecosystem functioning. Furthermore, plant physiological functions including root development, nutrient uptake and photosynthesis are strongly modulated by soil thermal conditions. Extreme temperatures can impair crop performance, destabilize microbial processes and threaten food security. Unlike earlier reviews that examine these processes in isolation, this paper offers an integrated synthesis of how soil temperature governs multifaceted interactions across soil–plant systems. This review identifies critical research gaps, including the long-term impacts of thermal fluctuations on soil structure and productivity, the adaptability of microbial communities to sustained warming and the temperature sensitivity of nutrient transformations. It also underscores the need for precision monitoring of soil thermal regimes. Addressing these gaps is essential for developing adaptive, temperature-informed soil and crop management strategies. Ultimately, the review advances a systems-based understanding of soil temperature dynamics to support sustainable agriculture in a changing climate.

Keywords: climate change; nutrient dynamics; plant growth; soil properties; soil temperature

Introduction

Agriculture, vital for life on earth, is shaped by several factors, including climate, soil and water. Among these, soil is fundamental to plant life, influencing every stage of growth through its physical, chemical and biological properties. The soil's physical environment is particularly crucial, as it regulates and modulates various soil processes. In the context of climate change-marked by rising global temperatures, soil temperature emerges as a critical variable. Governed primarily by solar radiation, soil temperature directly influences atmospheric temperature, with more than half of the solar energy received by earth absorbed by the soil and ocean (1).

Soil temperature regulates essential biological and biochemical processes such as seed germination, root elongation, microbial metabolism and nutrient dynamics (1). It plays a pivotal role in sustaining soil health by driving microbial activity, organic matter decomposition and nutrient cycling, all of which are crucial for plant growth and disease resistance (2). For example, a 10 °C rise in soil temperature significantly accelerates plant biochemical processes, underlining its agricultural significance (3).

This thermal factor is intricately linked to all soil processes-physical, chemical, biological and biochemical influencing microbial and enzymatic activity, mineralization and nutrient availability. Additionally, soil aeration, moisture retention, humidity and the efficiency of fertilizers and pesticides are also temperature-dependent (4). Plants and microbes perform optimally within specific temperature ranges; deviations may adversely affect their physiological functions. Soil temperature, as a determinant of the soil's energy balance, varies with the angle and intensity of solar radiation, thus influencing diurnal, seasonal and annual heat flux patterns. These variations affect energy storage, heat flow and land–atmosphere interactions (4). Moreover, it influences subsurface heat transmission and surface latent heat exchange, both of which are essential for energy partitioning in agroecosystems (5,6).

In the rhizosphere, soil temperature governs critical processes like root respiration, mineral weathering and nutrient mobility. However, the rhizospheric response to temperature changes is buffered compared to bulk soil due to active root respiration driven by photosynthesis (7). Still, temperature remains a decisive factor for microbial proliferation, organic matter decomposition and the release of plant-available nutrients (8). Consequently, it shapes soil's physical integrity, nutrient chemistry and microbial ecology (9). Under a warming climate, rising air and surface temperatures shift soil thermal regimes, thereby altering Soil Organic Matter (SOM) turnover, nutrient cycling and microbial functions (10,11).

Understanding these soil thermal dynamics is imperative to mitigate climate change's adverse effects on soil functioning and crop productivity (12). While soil temperature influences are often studied in isolation within specific climatic regions, this review adopts a global perspective encompassing tropical, temperate and other agroecological zones. This approach ensures broader contextual relevance and allows for a more comprehensive synthesis of temperature-related soil and crop responses across diverse agricultural systems.

Despite numerous studies on individual soil processes, a synthesis that critically links temperature fluctuations especially those intensified under current climate scenarios to the interconnected triad of soil physical, chemical and biological properties remains scarce. This review addresses that gap by analyzing the multifaceted influence of soil temperature on soil health and its cascading effects on crop growth. It explores fundamental questions such as how does soil temperature alter microbial and enzymatic functions, in what ways does it regulate nutrient cycling and organic matter turnover and how do these changes ultimately affect plant productivity.

Unlike earlier reviews that often focus on isolated components, this paper integrates diverse findings to offer a holistic view of temperature-driven shifts across soil systems. In doing so, it presents a critical synthesis of current knowledge and identifies key research gaps, including the long-term impact of thermal fluctuations on soil structure and crop yields, the adaptability of soil microbial communities to sustained warming, the temperature sensitivity of nutrient transformations and the need for precision monitoring of soil thermal profiles. These insights are crucial to guide future research and develop innovative, temperature-informed soil and crop management practices. Ultimately, the review promotes sustainable agricultural practices that consider soil temperature management as a key strategy to enhance and sustain soil health and productivity under changing climates.

Soil temperature impact on soil physical characteristics

Soil temperature is a critical environmental driver that directly and indirectly affects the physical properties of soil. These properties include aeration, moisture retention, texture, structure and colour, which not only determine soil vitality but also significantly influence crop productivity. Understanding how temperature variations, especially under climate change scenarios, alter these attributes is essential for developing sustainable soil and crop management strategies.

Soil aeration

Soil aeration refers to the exchange of gases, particularly oxygen (O_2) and carbon dioxide (CO_2), between the soil and the atmosphere. It is vital for root respiration, microbial metabolism and overall soil health, making it a key indicator of the soil's suitability for crop growth (13). Soil temperature influences aeration by altering the pore structure, soil moisture content and microbial respiration rates. As temperature increases, microbial and root respiration rates rise, increasing CO_2 efflux from the soil (14-16). This rise is partly due to enhanced activity of extracellular enzymes that degrade complex organic compounds, particularly within the 10 °C to 28 °C range (17).

Warmer soils also result in higher microbial oxygen consumption, which can lead to local oxygen depletion in poorly ventilated soils, thereby restricting aerobic processes and root function. The variability in soil respiration is influenced by a combination of soil moisture, temperature and microbial community dynamics. Notably, warming induces shifts in microbial diversity and metabolism, favoring communities with high G+C DNA content that are more thermostable than A+T-rich genomes (18). This compositional shift is often accompanied by functional changes: warming upregulates genes involved in the degradation of recalcitrant carbon compounds (e.g., vanA, mnp) while downregulating genes for labile carbon-degrading enzymes (e.g., mannanase, xylanase), signaling a microbial shift toward complex substrates (19). Such substrate-driven responses, possibly linked to the expansion of C_4 plant species under warming, may undermine long-term soil carbon stability.

Furthermore, warming enhances the decomposition of cellulose by approximately 13 %, elevates CO_2 production by around 10 % and increases denitrification rates by about 12 %, all of which contribute to greater carbon loss and altered nitrogen dynamics. These changes in microbial gene expression and respiration under warming conditions highlight the intricate interplay between temperature, soil aeration and microbial ecological function (20). Management practices such as reduced tillage, organic matter amendments and residue retention can help mitigate these effects by preserving soil structure and maintaining favorable aeration in a warming climate (21-23).

Soil moisture

Soil temperature and soil moisture exhibit a dynamic and reciprocal relationship. Generally, higher temperatures increase evapotranspiration and reduce soil moisture availability, especially in arid and semi-arid environments. This inverse relationship is well documented, where increased soil temperatures lead to reduced soil water potential, especially in dry regions (24). Additionally, extreme temperatures can inhibit photosynthesis and other plant physiological processes through their effect on moisture availability (25). In sandy soils, higher soil temperatures accelerate moisture loss through evaporation and in other soils, they reduce the soil's capacity to retain water (26,27). Moreover, temperature-induced changes to soil structure can further affect water retention, as shown in clay-rich soils (28).

To quantify the relationship between soil heat dynamics and moisture buffering capacity, the following empirical equation has been used (29):

$$Q = 4.2 \times 10^3 \times V \times (0.2 + W) \times \Delta T \qquad \text{Eqn. 1}$$

Where

Q = heat energy (J)

V = soil water volume

W = water-holding capacity factor

ΔT = temperature change

This equation illustrates how soil moisture acts as a thermal buffer, modulating the heat absorbed and stored in the soil. For instance, if a soil contains 10 L of water ($V = 10$), has a water-holding capacity factor $W = 0.25$ and experiences a temperature increase of 5 °C, then the heat energy absorbed would be $Q = 4.2 \times 10^3 \times 10 \times (0.2 + 0.25) \times 5 = 94500$ J, demonstrating the significant role of moisture in soil thermal dynamics.

Increasing soil temperature also reduces Water Use Efficiency (WUE), particularly in arid zones, which necessitates soil temperature management strategies (e.g., mulching, residue retention) to optimize irrigation and minimize evaporative losses (30).

Beyond physical impacts, reduced soil moisture significantly affects chemical and biological soil processes. Limited water availability restricts the diffusion of dissolved nutrients such as nitrate (NO_3-) and phosphate (PO_4^{3}-), thus impeding root uptake and altering the stoichiometry of soil solutions. Drier conditions also concentrate salts in the soil, intensifying osmotic stress and reducing the rates of nutrient mineralization (31). Microbiologically, water scarcity pushes microbial communities into dormancy or selectively favors xerotolerant taxa such as actinobacteria, which shift decomposition toward recalcitrant carbon breakdown pathways (32). These biological and chemical responses highlight how temperature-induced moisture stress feeds back into nutrient cycling efficiency and microbial activity, ultimately influencing soil fertility and plant productivity. Thus, the interplay between soil temperature and moisture not only governs energy balance and water retention, but also cascades into nutrient cycling and microbial ecosystem function, reinforcing the need for integrated soil-climate management approaches.

Soil texture

Soil texture, defined by the relative proportions of sand, silt and clay, is subject to modification under varying temperature regimes. Temperature can affect the mineralogical stability and physical breakdown of soil particles. For example, in clay-rich soils, high temperatures may cause 2:1 clay mineral to lose interlayer water, compacting the structure and decreasing clay content while increasing silt proportions (33). Similarly, sandy soils may undergo disaggregation into finer particles under elevated temperatures (34). Further research supports these findings, with increased soil temperatures associated with reductions in both clay and sand fractions and a relative increase in silt content (23).

Studies on soil temperature prediction in semiarid regions also indicate that textural changes may significantly impact thermal conductivity and water movement. For instance, experimental warming studies have shown that soil exposed to 5-8 °C above ambient temperature for more than 12 months experienced a measurable decline of 3-5 % in clay fraction and a 4-6 % increase in silt content (35). These alterations can influence key hydrological processes such as infiltration rate, capillary rise and hydraulic conductivity. Moreover, clay mineral transitions under prolonged warming may also affect Cation Exchange Capacity (CEC), further modifying nutrient retention and leaching behaviour (36). Such changes have cascading implications for soil porosity, root penetration resistance and water-holding capacity parameters critical for maintaining productive agroecosystems in the face of climate variability.

Soil structure and aggregate stability

Soil structure refers to the arrangement of soil particles into aggregates, which is essential for water retention, aeration and resistance to erosion. Soil temperature, in combination with moisture, plays a significant role in modulating soil aggregation. Seasonal fluctuations in temperature cause soil particles to expand and contract, affecting inter-particle bonding and clay dispersion. Higher temperatures have been associated with soil degradation and loss of organic carbon, reducing structural integrity (37). Aggregate stability tends to decline as temperature rises up to 28 °C (38), although some studies suggest an increase at around 30 °C due to thermal effects on iron and aluminium oxides that help stabilize aggregates (39). The optimal temperature range for maintaining soil aggregate stability is approximately 15 °C to 25 °C (40). Temperatures above 30 °C may lead to breakdown of aggregates due to decreased cohesion among particles (41). Furthermore, microbial activity-central to aggregate formation and stabilization is itself highly sensitive to thermal conditions (42). Elevated temperatures promote clay mineral dehydration, leading to structural collapse (23).

The influence of temperature on CEC varies with soil mineralogy and moisture conditions. In kaolinitic or highly weathered tropical soils, CEC often decreases with increasing temperature due to collapse of clay layers and reduced surface charge density. In contrast, in soils rich in smectite or vermiculite (2:1 clays), moderate warming can increase CEC temporarily by enhancing the expansion of clay interlayers and ion exchange activity-especially under moist conditions (43). However, prolonged high temperatures (>35 °C) tend to reduce CEC even in these soils by promoting irreversible clay dehydration and organic matter loss (36). This highlights the importance of clay type and thermal exposure in determining the direction and magnitude of CEC change under warming scenarios. Thus, maintaining soil temperature within optimal ranges is key to preserving structural stability and ensuring favourable conditions for root growth, nutrient retention and water infiltration.

Soil colour

Soil colour, an often-overlooked physical property, significantly influences thermal dynamics. Dark-coloured soils rich in organic matter absorb more solar radiation and tend to reach higher surface temperatures compared to light-coloured soils (26,44). These thermal differences affect diurnal and seasonal soil temperature profiles, which can further influence microbial activity, evaporation and nutrient cycling. In warmer periods, dark soils not only retain more heat but may also exacerbate surface warming, contributing to localized heat stress (45).

The influence of colour on heat absorption makes it both a determinant and a consequence of soil temperature regimes. Hence, soil colour contributes to thermal behaviour, influencing a range of biophysical processes and reinforcing the importance of organic matter in climate adaptation strategies.

Soil temperature impact on soil fertility

Soil temperature is a crucial factor influencing soil chemical properties, including pH, Electrical Conductivity (EC), CEC and nutrient transformations. It modulates biological and biochemical interactions that directly affect soil fertility and plant nutrient availability.

pH and EC

Soil temperature exerts a strong influence on pH and salinity dynamics. Warmer soils often become more acidic due to accelerated organic acid decomposition, as observed between 25 °C and 39 °C (46). A previous study reported a decline in EC in sandy soils with increasing temperature (47), while another study noted that high temperatures enhance salinization through evaporation and upward water movement (48). Subsequent studies further established that elevated temperatures increase salinity risks by enhancing salt accumulation at the surface through capillary rise (49,50).

CEC

CEC, essential for soil nutrient retention and exchange, is affected by temperature-induced changes in colloidal structure and organic matter content. A demonstration indicated that rising soil temperatures reduce CEC, especially in soils, rich in allophane, imogolite and humus (51). Above 35 °C, organic matter decomposition is enhanced, reducing surface charge and cation-holding capacity (52). As temperature affects ion mobility, it alters the rate and equilibrium of cation exchange reactions (53), with implications for nutrient availability and leaching losses.

Soil Organic Carbon (SOC)

SOM decomposition is highly temperature-sensitive. Low temperatures limit microbial degradation of SOC, whereas higher temperatures accelerate mineralization, leading to reduced carbon stocks and increased CO_2 emissions (54-57). Notably a previous study reported that arable lands under aridic-cyric regimes exhibited higher SOC density, whereas in warmer, moister regimes, non-arable lands retained more SOC due to reduced disturbance (58). Surface layers respond rapidly to temperature fluctuations, while deeper layers-more thermally stable determine SOC persistence (59). Temperature-driven enzyme activities influence labile carbon turnover, though oxidoreductase activity exhibits an inverse trend with rising temperature (60). At 10-50 °C, total and humic organic carbon decline, while water-soluble organic carbon increases, demonstrating higher thermal stability and microbial resistance (61).

However, recent works suggests that certain soils may overestimate SOC vulnerability to warming, particularly those with stabilizing mineral phases (62,63). Cold, moist regions exhibit dense organic layers and peat accumulation, contributing to high-latitude SOC gradients, where over 500 Pg of C is stored globally (64). Temperature sensitivity of SOC decomposition, often expressed as Q_{10}, indicates that soils with higher Q_{10} values are more vulnerable to temperature-induced carbon losses (65). Agricultural practices, such as deep tillage and residue management, significantly influence soil thermal regimes and hence carbon flux (51).

Nitrogen dynamics

Nitrogen mineralization and uptake are tightly governed by soil temperature. According to the Arrhenius principle, N mineralization rates approximately double with every 10 °C increase (66). Temperature affects mass flow, diffusion and enzymatic reactions in both soil and water (67), influencing urea hydrolysis and ammonium conversion (68,69). Seasonal temperature changes alter microbial-driven anaerobic mineralization of N and P, with higher temperatures often reducing microbial activity and N availability (70). Both organic and inorganic nitrogen uptake are temperature-dependent (71). While crop residues enhance N release, higher temperatures can suppress this process (72).

Warmer conditions favor non-N-fixing plants and excessive heat may induce nutrient depletion (73,74). Moreover, thermal gradients influence moisture-driven nutrient transport (75). Nitrogenase enzymes operate optimally at ~25 °C, with activities sustained up to 42 °C (76). In cucumber rhizospheres, (77) found that 40 °C enhanced N mineralization, whereas 28 °C preserved N through microbial stabilization. Warmer winters, causing reduced snow cover and more freeze-thaw cycles, further reduce nitrate availability (78). At 27-29 °C and again at 36-38 °C, N and P availability decline (58,79), while elevated temperatures can skew soil N:P ratios, increasing the risk of P limitation (80).

Despite increased mineralization at higher temperatures, nutrient loss through volatilization, denitrification and leaching may offset gains (81). For instance, a 2 °C increase under moisture-stress conditions significantly reduced nitrogen release in organically treated soils, attributed to decreased microbial activity and higher gaseous losses although irrigation and decomposer microbial inoculants mitigated this effect (82).

Phosphorus dynamics

Phosphorus availability is similarly temperature-sensitive. Below 15 °C, phosphorus release from organic matter slows significantly (83). In contrast, temperatures between 5 °C and 25 °C enhance water-soluble P (60). Elevated temperatures (33-38 °C) increase P loss by 16-20 %, followed by a slight decline above 38 °C (58,84). Warmer climates coupled with high rainfall tend to lower available P due to increased leaching (85). Soil temperature affects not only P mineralization but also its sorption-desorption dynamics (86), root architecture and mycorrhizal symbioses, all of which determine P uptake efficiency.

Potassium dynamics

Soil temperature directly influences potassium availability and uptake by modifying root physiology and microbial interactions. Warmer soils enhance K mineralization, desorption and microbial activity resulting in greater K mobility and crop uptake (84). However, soil K can also be lost via leaching under excessive heat and rainfall (87). Seasonal patterns influence K distribution: during *Kharif*, surface K concentrations increase with topsoil warming due to mineral release and microbial turnover (79).

Soil temperature impact on soil biological properties

Soil organisms and microbial activity

Soil temperature is a critical regulator of biological processes, influencing the activity, diversity and abundance of soil organisms that drive decomposition and nutrient cycling. Warmer temperatures generally enhance microbial activity, increasing the rate of organic matter breakdown and nutrient mineralization (88,89). Below 10 °C, microbial processes slow significantly and may cease at freezing, whereas optimal functioning occurs between 10 ° C and 35.6 °C (56,90). Soil macro-organisms, such as earthworms and arthropods, also display peak metabolic activity between 10 °C and 24 °C (21).

Soil respiration, a measure of microbial activity, rises with increasing temperature due to stimulated enzyme kinetics and microbial metabolism (21,90). Nitrogen mineralization is particularly responsive to temperatures between 20 °C and 25 °C (91). A 10 °C rise in soil temperature has been shown to alter microbial communities and root architecture, influencing plant biomass (89). Optimal microbial activity is observed between 25 °C and 35 °C, while prolonged exposure to elevated temperatures can shift microbial composition and reduce nutrient accessibility (84,92). For example, under a +2 °C temperature scenario, applying decomposer microbes and irrigation in maize stover plots enhanced potassium availability-suggesting an adaptive strategy for climate resilience (93).

Soil temperature thus governs microbial growth, enzymatic function and metabolic rates, which are essential for organic matter decomposition and nutrient turnover (94).

Organic matter decomposition

Temperature strongly regulates organic matter decomposition, a fundamental process in nutrient cycling and carbon turnover. Decomposition rates decline under freezing conditions, resulting in organic matter accumulation (56,95). Below 15 °C, microbial metabolic activity decreases, slowing the decay process. Conversely, temperatures between 21 °C and 38 °C accelerate decomposition due to enhanced substrate diffusion and microbial activity (96).

High temperatures can also shift microbial diversity and gene expression, impacting enzymatic pathways involved in decomposition (84). Although decomposition increases with temperature, the stability of certain organic matter fractions may buffer losses in soils rich in organo-mineral associations.

Plant growth and development

Soil temperature directly affects plant physiological processes, including seed germination, root development and nutrient uptake. Optimal soil temperatures (25-30 °C) support rice seedling emergence, while extremes reduce germination rates (96). Root and shoot growth are temperature-dependent, highly favoured with warmer soils improving nutrient and water absorption and enhanced soil aeration (97,98). Soil temperature also influences chemical reactions and microbial activity critical to plant nutrient supply (99, 100).

Low temperatures can suppress root development and limit nutrient translocation to aboveground tissues (93,101). A soil temperature of 10 °C can reduce nutrient concentrations in plant tissues, while increasing it from 12 °C to 25 °C promotes root growth and dry matter accumulation (102,103). Physiological disorders, such as tuber deformation in potatoes, may arise under high soil temperatures (104,105). Additionally, species-specific responses have been noted-for instance, low temperatures encourage root elongation, while warmer conditions promote branching in succulent plants (106).

Photosynthesis and plant productivity tend to decrease at temperature extremes (<9 °C or >50 °C), underscoring the need for maintaining soil temperatures within optimal biological windows (105).

Water and nutrient uptake

Soil temperature modulates water and nutrient uptake by influencing root physiology, microbial-mediated nutrient transformations and soil water viscosity. Warmer soil enhance microbial activity, which increases nutrient solubilization and availability (69). Elevated temperatures improve root elongation and branching, facilitating greater absorption of water and nutrients (72).

At lower temperatures (0-10 °C), water viscosity increases, which impedes root water and nutrient uptake (98). This also affects stomatal conductance, reducing transpiration and nutrient transport (100). Conversely, at optimal temperatures (~23 °C), plants absorb more micronutrients such as Cu, Zn and B under moist conditions compared to cold or dry soils (107). However, beyond 38 °C, evapotranspiration increases substantially, reducing soil moisture availability and nutrient uptake efficiency (108,109).

Soil temperature also influences seed dormancy and germination behaviour in weed species. For instance, *Bromus sterilis* shows delayed germination below 25 °C due to temperature-induced dormancy (25). Thus, the thermal environment of the soil plays a critical role in shaping water relations, nutrient dynamics and overall plant performance.

Soil temperature exerts profound effects on the biological functioning of soils, encompassing microbial activity, organic matter turnover, plant growth and nutrient uptake. These responses are highly temperature-sensitive and exhibit species- and site-specific variations. Table 1 synthesizes key temperature thresholds and their biological implications, serving as a practical guide for managing thermal dynamics in agroecosystems. Soil temperature-driven shifts in microbial activity, nutrient dynamics and SOM decomposition are illustrated in Fig. 1, which contrasts key soil processes under low and high temperature regimes, emphasizing their implications for soil health and crop productivity. Understanding these interlinked processes is essential for improving soil health, crop productivity and ecosystem resilience under changing climate conditions.

Future climate scenarios and adaptation

Climate models project a significant rise in global mean surface temperatures-ranging from 1.5 °C to 2.5 °C by 2050-which will consequently elevate soil temperatures, especially in tropical and arid regions. Soil warming is expected to be 3 °C to 4 °C in parts of sub-Saharan Africa, South Asia and Latin America, where sparse vegetative cover and intense solar radiation amplify heat absorption (110). Such elevated soil temperatures have serious implications for SOC stability, particularly in areas already facing low organic matter input, high rates of mineralization and limited moisture retention. In contrast, high-latitude ecosystems with peat-rich soils, such as tundra and boreal forests, may release massive quantities of long-stored SOC as permafrost thaws, posing a global feedback risk (111).

Among the most effective strategies for mitigating SOC losses under warming conditions is mulching, which insulates the soil surface, regulates temperature and conserves moisture. Recent studies from North China have shown that plastic mulching increases soil temperature by 2.3-4.0 °C, accelerating crop development in cool seasons (112). Conversely, straw mulching can reduce soil temperature by 0.4-4.7 °C, buffering crops against heat stress during hot seasons and improving water retention. In Kenya, applying 12 t⊠ ha^{-1} of maize stover mulch reduced the soil temperature differential between highland and lowland sites from 7.8 °C to 2.3 °C, enhancing tuber emergence and crop yield (113). These temperature-modulating effects of mulching are especially relevant in semi-arid and tropical systems where thermal stress undermines SOC stabilization and crop productivity.

In addition to mulching, the integration of cover crops, conservation tillage and organic amendments is essential for building soil resilience. Conservation agriculture practices-characterized by minimal soil disturbance, residue retention and crop diversification-have demonstrated substantial benefits under warming scenarios. A global meta-analysis reported that conservation agriculture improved wheat yields by 9.3 %, enhanced microbial diversity and sustained SOC levels despite temperature increases (114). The application of organic amendments such as compost, manure and biochar further supports SOC persistence by enhancing aggregation and promoting organo-mineral associations, which protect carbon from microbial decomposition (115).

Table 1. Influence of soil temperature on the soil health

Soil temperature (˚C)	Activity	References
	Soil physical	
15 - 25	Optimum for soil aggregate stability	(35)
30	Increase aggregate stability in Fe/Al rich soil types	(34)
>30	Disrupt soil aggregation	(52)
	Soil chemical properties	
25 - 39	Increase Soil pH due to organic acid decomposition	(39)
> 35	Decline in SOM content	(73)
0 - 40	N mineralization rate will be double for every 10°C increase up to 40˚C.	(56)
10 - 50	Reduce accumulation of total organic carbon, easily oxidized organic carbon and humic carbon.	(52)
25	Optimal for nitrogenase activity & persisting up to 42°C	(66)
27 - 29	High N availability in soil	(49)
36 - 38	High P availability in soil	(70)
<=15	Reduce P availability in soil	(74)
0 - 40	Plant biochemical reactions rate will be accelerated for every 10°C increase	(3)
	Soil biological properties	
>35	Decrease in SOM content	(84)
10 - 0	Decrease in soil microbial activity & freeze at zero.	(75)
10 - 36	Optimal range for soil microbes functioning	(75)
20 - 25	Quickens nitrogen mineralization.	(83)
10 - 24	Increase soil macro-organisms' metabolism	(18)
<15	Decrease in microbial metabolic activity and organic decomposition	(73)
25 - 35	Microbial activity and growth are best	(84)
21 - 38	Faster diffusion of soluble substrates boosts microbial decomposition	(52)
	Plant growth and development	
25 - 30	Optimal for rice seedling emergence	(90)
<9 & >50	Reduces plant growth	(20,70)
0 - 10	Thicker soil water and reduced root nutrient decreases nutrient concentration in tissues & reduce root growth	(94)
12 - 25	Increase root activity and lateral root development	(95)
23	Increase in uptake of Zn, Cu & B in plants	(101)
>38	Decrease soil water uptake due to increased evapotranspiration	(102)
<25	Increases seed dormancy and delays germination in *Bromus sterilis*, a noxious gross weed.	(72)

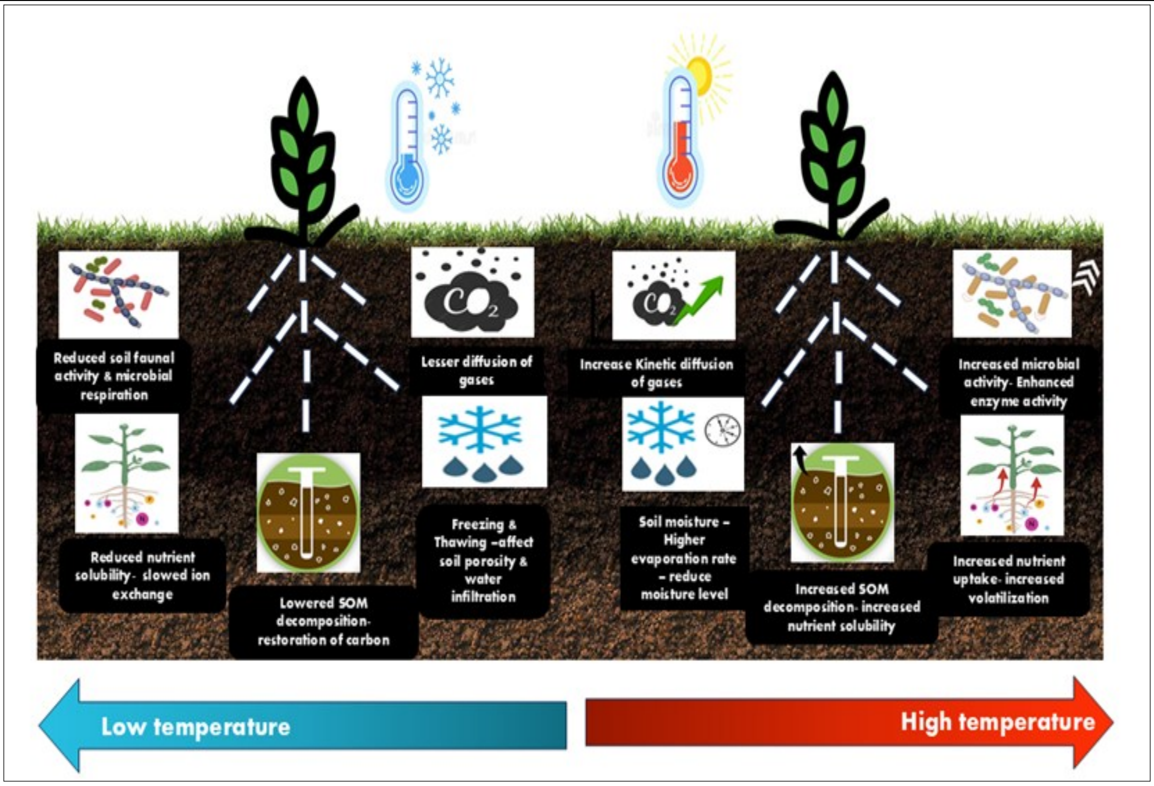

Fig. 1. Temperature driven impacts on soil processes and plant nutrient dynamics.

Moreover, breeding and deployment of heat-tolerant crop varieties represent a biological adaptation strategy. Crops with deeper roots and enhanced canopy temperature depression maintain productivity under heat stress while contributing more carbon to deeper soil layers. For instance, the ICPV 25444 pigeon pea cultivar, developed by ICRISAT, tolerates temperatures up to 45 °C, enabling year-round cultivation in semi-arid Indian regions and improving belowground carbon inputs (116). Similar progress has been made in maize and rice breeding, focusing on heat-shock protein expression and increased root biomass to enhance resilience and SOC accrual under elevated temperatures (117).

Overall, these adaptation strategies-when tailored to regional agroecological conditions-can substantially mitigate the negative impacts of warming on soil properties. Incorporating soil temperature management into agricultural planning is not just an option, but a necessity for sustaining soil fertility, productivity and climate resilience in the coming decades.

Conclusion

Soil temperature plays a pivotal role in regulating the physical, chemical and biological properties of the rhizosphere. It governs essential processes such as nutrient mineralization, organic matter decomposition, microbial metabolism, root development and the availability of air and water. As soils act as a significant thermal reservoir, the stored heat influences the rate of biological activities, particularly enzymatic and microbial functions that are fundamental for plant nutrition and productivity. Optimal soil temperature ranges enhance microbial activity, support effective nutrient cycling and stimulate healthy root growth, thereby contributing to improved plant vigor and sustainable yields. However, deviations from this optimal range-whether due to seasonal extremes or anthropogenic climate change-can disrupt these processes, resulting in nutrient imbalances, reduced crop productivity and altered ecosystem functioning. Adopting practices such as mulching, cover cropping, biochar addition and conservation tillage can help regulate soil temperature and buffer its adverse effects under changing climatic conditions.

Future directions

Future research should prioritize understanding how climate change-induced shifts in soil temperature affect soil health, crop productivity and ecosystem resilience across different agroecological zones. Emphasis should be placed on developing temperature-resilient crop varieties and refining soil management strategies-such as mulching, biochar application and cover cropping-that can buffer thermal extremes. Investigating the response of microbial communities and enzyme-mediated nutrient transformations under varying temperature regimes is critical to predict changes in nutrient cycling and carbon sequestration. Furthermore, integrating emerging technologies like real-time soil temperature sensors, remote sensing and data-driven modelling can enhance precision in monitoring and managing soil thermal dynamics. Interdisciplinary collaboration across soil science, agronomy, climatology and digital agriculture is essential to build thermally adaptive and sustainable agricultural systems in the face of global climate variability.

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Authors' contributions

JD and DG contributed to the review and conceptualization of the manuscript. MM, PM and KS were involved in manuscript editing. All authors read and approved the final version of the manuscript.

Compliance with ethical standards

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