



The Role of Earth Warmth in Soil Fertility

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Abstract:

Soil temperature impacts terrestrial ecosystem fertility and regulates mineral weathering and soil organic matter (SOM) turnover. It affects nutrient transformation like N, P, and K, which are crucial for plant growth. However, the variation in soil temperature across different climates and soil types is often overlooked in global fertility assessments. Soil temperature ranges from 75 °C in deserts to 0 °C in polar areas, with annual variations being more significant than air temperature in tropical regions. It also varies by depth, often exceeding air temperature in tropical and polar zones. Increased warming and vegetation do not ensure shorter fallow periods or enhanced soil fertility. Research has mainly concentrated on permafrost and elevation, revealing a gap in understanding. Temperature-sensitive processes like microbial activity and nutrient release are also influenced by soil moisture. In the southern Great Plains, assessments indicate that drought from global warming may hinder nutrient acquisition, delaying ecosystem recovery. (M. Melillo et al., 2017)(Salazar et al., 2020)(S. A. Johnston et al., 2018)

Keywords: Soil temperature, soil organic matter, Soil Fertility, Mechanisms.

1. Introduction

Soils serve as an essential resource for terrestrial productivity and ecosystem functioning, providing a fundamental substrate for crop and tree growth, habitats for soil-borne organisms, and buffering and detoxifying chemicals rather than letting them leach directly into waterways. The combination of terrestrial environment above ground and soil system below ground determines biodiversity patterns within ecosystems, contrasting with patterns of terrestrial aboveground productivity. Soils amplify



temperature extremes during the growing season relative to the air above and delay warming trends in temperate regions already undergoing climate changes.

Heard from farmers and agronomists across many regions of the planet, warmer soils stimulate soil fertility was a widely accepted idea long before scholars began examining further the mechanisms behind the linkage. Active research in recent years continues to confirm various patterns that soil fertility indeed increases as the soil warms; specific climate control plateaus of soil fertility and crop productivity at temperature 0-20°C for permanent wet biomes in temperate, tropical, and arid environments support the hypotheses of soil temperature influencing soil fertility both at the macro and micro scales (M. Melillo et al., 2017).

2. Conceptual Framework: Temperature and Soil Fertility

Thermal regimes in soils differ significantly across climates and soil types, affecting fertility and nutrient dynamics. Seasonal heating in temperate and tropical climates enhances nutrient mobilization via organic-matter mineralization, usually faster than new organic matter formation. In seasonal wet-arid and semihumid zones, sparse vegetation contributes additional heating, while seasonally frozen regions display uneven fertility based on temperature. Soil temperature also varies with water content, where moisture dynamics and evaporation differ by environment. In dry arid areas, limited rainfall leads to deep moisture screening, which hampers thermal wave penetration. Climate change may expand optimal thermal-biofertility conditions and modify soil temperature patterns. Warmer soils improve nutrient mobilization through mineral weathering, facilitating nutrient release into the soil for plants. Increased temperatures boost microbial metabolism, enhancing organic-matter decomposition and nutrient turnover rates, assuming other conditions support microbial activity. Stabilization of organic matter by sorption and chemical association plays a critical role in retention, while warmer soils lead to decreased stable organic-matter accumulation and greater release of dissolved organic carbon, nitrogen, and phosphorus, particularly in arid regions during dormancy and thawing. (E. Taylor et al., 2021)

3. Physical and Chemical Mechanisms Linking Warmth to Soil Fertility

Temperature affects soil processes crucial to moisture dynamics, mineral availability, gas fluxes, and organic matter. Colder soils hold microbial nutrients, while warming boosts mineral weathering, cation exchange, organic matter stabilization, and nitrogen cycling. Soil-water contact properties drive many reactions. Intense rain leads to deep drainage at high temperatures and lateral flow at low temperatures. Infrequent light rain encourages surface storage and runoff. Thermally controlled water management impacts



moisture and soil temperature, influencing fertility and carbon balance. A second-order model simulating soil-water and temperature dynamics helps analyze large watersheds under different grazing strategies. Climate-change forest models offer constraints, while global databases highlight temperature's influence on fertility across various climates. Early inland Australian soils, though widely spread, show low fertility due to initial low temperatures and high pressure creating acidic saline conditions. Elevated surface temperature occurs during wet cycles compared to powdered quartz. Humic evaporates likely predate acidic conditions, and concentrated soils developed lead to nutrient depletion, impacting agriculture in pH 5 to 6 grassland savanna environments under varied thermal regimes. (M. Melillo et al., 2017)(Salazar et al., 2020)

3.1. Soil Moisture Dynamics and Evapotranspiration

Soil moisture is of paramount importance in regulating the partitioning of incoming radiation into latent and sensible heat, as it exerts a major influence on evaporation, transpiration, and the associated energy and mass fluxes within the soil-vegetation-atmosphere system. It determines and modulates plant growth and constitutes one of the principal factors affecting crop yield and food production. The root-zone soil moisture determines water availability for photosynthesis, which is ultimately regulated by plant stomatal conductance. Furthermore, plants efficiently extract water through the rooting system from the deeper soil layers, thus reducing the precipitation that reaches the groundwater reservoir. Evapotranspiration returns about 60% of the water intercepted as land precipitation back to the atmosphere, highlighting the feedback loop between soil moisture and vegetation in terrestrial water and energy cycles (Korres, 2013). Soil moisture exhibits a high degree of spatial and temporal variability, governed by soil heterogeneity, topography, land cover, and meteorological conditions.

Soil-water evaporation and the associated transfer of mass and energy remain critically important in influencing a wide spectrum of environmental processes, with impacts that span microbial communities through to continental-scale weather patterns and even climate. Elucidating the dynamics of water evaporation from the soil remains an outstanding challenge; indeed, the overarching picture of soil-water evaporation is often, simplistically, reduced to the surface energy balance, with the underlying dynamic processes either not represented or inadequately observed or measured (L. Heitman et al., 2008).

3.2. Mineral Weathering and Nutrient Release

Mineral weathering plays a vital role in the release of nutrients that are essential for soil fertility and plant growth (Doetterl et al., 2018). Various anthropogenic processes such



as land conversion and erosion can influence patterns of weathering, particularly in landscapes that are currently undergoing erosion where the weathering front is situated near the soil surface; such influences also alter the cycling of nutrients. Elevated temperatures are projected to increase weathering rates, yet the relationship between climatic warming and weathering is highly variable among different climates. Different climate zones undergo different degrees of weathering, with each affected by climatic changes in distinct manners. In addition, the age of a given soil profile—young, intermediate, or old—dictates both mineral reactivity with respect to nutrients and the stabilization of organic carbon associated with mineral surfaces. The dominance of specific biological agents, such as bacteria or fungi, governs the pathways of organic matter decomposition and the overall cycling of nutrients in soils, thereby influencing both the mass and turnover of soil organic carbon. Consequently, the analysis of weathering trajectories throughout various geomorphic and climatic contexts is essential for understanding patterns of nutrient availability and the evolution of soil systems.

3.3. Microbial Activity and Decomposition Rates

Higher temperatures increase biological activity and organic matter decomposition, significantly affecting decomposed organic matter and soil organic carbon loss. Warming raises respiratory costs for soil microbes, leading to higher microbial carbon-use efficiency, which slows soil organic carbon loss. It enhances fungal spore production and plant litter decomposition, causing plants and fungi to produce more secondary carbon skeletons, including harmful phenolic compounds affecting soil biota. This can create less favorable soil biological conditions for carbon preservation. Pold et al. (2016) suggest these findings aid in understanding soil and microbial community responses to warming at the ecosystem level. In soils warmed by geothermal heat over centuries, a persistent increase in microbial respiratory costs has been observed, affecting substrate use efficiencies and increasing carbon losses. Warming alters substrate composition, increasing the availability of carbon-rich compounds, which modifies community structures and reduces substrate use efficiencies. Although microbial biomass declines at higher temperatures, greater carbon allocation into non-structural and secondary metabolites may result in a higher overall carbon loss. Warming releases previously inaccessible carbon stocks, leading to total carbon losses surpassing microbial carbon demand and emphasizing the need for a comprehensive view of microbial community changes. The composition and metabolic capabilities of microbes in naturally warm soils, their gene abundance related to carbon acquisition, and comparisons between



climatically warmer and historically/anthropogenically warmed sites are underscored. (Pold et al., 2016)(Marañón Jiménez et al., 2018)

3.4. Organic Matter Stabilization and Humification

Soil organic matter (SOM) is a heterogeneous mixture comprising decomposed dead plant and animal residues, living microorganisms, and humus. It plays a vital role in maintaining soil fertility. Several processes contribute to the formation and stabilization of organic matter within the soil. Decomposition is a process in which edaphon (fungi, bacteria, protozoa, and micro-arthropods) break down dead biomass. Decomposition rates are modulated by moisture and temperature, type of substrate, chemical composition of plant residues, and environmental factors. Under anaerobic conditions, SOM undergoes a process called humification, which results in the formation of substances resistant to further microbial decomposition. Climate change is expected to raise global average temperatures and induce changes in precipitation that will affect soil moisture and drying cycles and, consequently, the agriculture sector. Analysis of historical records of global temperature and rice productivity indicated significant temperature-induced shifts in rice-fallow soil fertility around 1861, suggesting that temperature has a significant impact on soil fertility (Jilling, 2019).

4. Temperature Regimes Across Climates and Soil Types

Soil temperature represents one of several physical measures critical to understanding soil fertility. Soil temperature affects several biologically mediated processes important for plant growth, including decomposition of soil organic matter, nutrient cycling, mineral weathering, and soil moisture dynamics. Soil temperature is closely connected to climate and vegetation type, and from these relationships, general knowledge is available on soil temperature regimes expected from given sets of climatic and vegetation conditions (E. Taylor et al., 2021).

Temperature of water from precipitation and thawing of snow reaches the soil in large part from its thermal capacity, which varies with both global and non- global climatic conditions (M. Melillo et al., 2017). Water below freezing maintains its temperature considerably longer than does water above freezing. Snow and ice therefore provide special conditions under freezing conditions in certain climates. Under non-freezing conditions, ground water and its temperature play a major role in the relationship. The role of ground water is especially important in glaciated and post-glaciated areas, where high deposit water contents are present (Salazar et al., 2020).

4.1. Seasonal Heating and Fertility Patterns: Independently of other factors, soil fertility varies across latitudes, having an intricate relationship with seasonally induced



temperature fluctuations. Important insights can be gained from global comparisons of different systems. In the temperate zones, where seasonal changes are often quite striking, fertility decreases with increasing latitude. Most of southern Canada and a substantial portion of northern Canada exhibits low fertility, although the predominant soil is fertile Chernozem (M. Melillo et al., 2017). Unlike the exposition of the predominant soil in the biome, a seasonal-transient description is preferable for defining soil temperature and fertility in Canada. Northern-most areas possess soils that do not melt sufficiently in spring in order for the temperature to rise to values that favor microbial activity and soil fertility, which can be considered another perspective for bottom-up approach of biomass production (Regina Boland et al., 2020).

Both in the tropics and dry areas, the decrease of fertility at the poles is, however, absent. Along the equatorial band, fertilization is nonexistent due to extremely little transfer of soil and biospheric material to the water and consequently litterfall and nutrient replenishment is as well. In dry areas such as mars-like conditions, new mineral elements and soil material are introduced.

4.2. Thermal Gradients in Soil Profiles

Temperature regimes across climates and soil profiles exhibit remarkably diverse patterns, resulting in varying soil fertility conditions and agricultural productivity. While temperate climates generally experience a broadening of the favourable period with warming, many equatorial regions and some polar and continental areas show different warming trends. For several important soils and systems, temperature fluctuations are examined at different depths. In tropical soils, an increased supply of nutrients is observed; in temperate systems, the extent of the favourable temperature regime and carbon accumulation may change, conditioning either favourable or unfavourable humidity contributions; and polar soils may remain inactive unexpectedly long after snow melting (Cary, 1966).

Soil does not simply respond to ambient temperature variations but develops specific thermal regimes depending on climatic and soil conditions. A typical surface-to-depth amplitude attenuation ranging from 20 to 50%, mostly limited to the upper decimetre, is characteristic of humid ecosystems; while a considerably higher attenuation of 80–90%, extending up to 50 cm, is detected in arid and semi-arid ecosystems. In tropical humid systems, a remarkable bi-modal behaviour occurs. This deepened, de-coupled thermal regime is attributed to an enhanced role of moisture-phase changes, with slower adjustments following the daily and seasonal temperature cycles. Temperature records



from well-instrumented sites illustrate these soil-response behaviours to complex climate changes.

4.3. Anthropogenic and Global Change Influences

It is important to recognize that temperature also plays a role in how anthropogenic activities and global change can influence soil dynamics. Growing human population and related development of industry and agriculture have increased demand for food production and subsequently altered soil systems, fertility, and health. Moreover, climate change caused by anthropogenic activities is affecting both soil moisture and temperature across soil regimes, impacting processes already discussed. Areas receiving increased precipitation have seen rising soil moisture leading to lower soil temperature, nutrient leaching, and soil organic matter decreased, whereas climate change has caused soil warming in semi-arid, alpine, and polar regions (M. Melillo et al., 2017).

As climate change progresses, soils situated on permafrost as well as organic matters in such soils will steadily increase temperature and accelerate decomposition. In addition to boosting N release, rising decompose-rate and temperature will result in greater land-plant biomass and above-ground N increment throughout Arctic region (Salazar et al., 2020). On a global scale, temperature increase of 0.5–6°C is projected, leading to 30–70% losses of soil organic carbon and threaten an additional 1.4 billion people living under water scarcity. This ACV region encompassing both sub-humid and semi-arid will shift towards drier and warmer and soils will experience severe decay of the organic C stock, soil fertility decline, and restoration period.

5. Empirical Evidence: Observations and Experimental Studies

Earth warming impacts global climate, temperature dynamics, terrestrial life, and ecosystem services essential for humanity, particularly soil fertility, which depends on climate. However, empirical evidence regarding soil temperature's direct effects on fertility is limited. High soil temperatures accelerate processes like moisture evaporation, weathering, biological activity, and organic matter stabilization while inhibiting those that reduce fertility. Modest warming can enhance nutrient availability, microbial respiration, organomineral complexes, and litter input, contributing to soil organic carbon stabilization via careful moisture management against rising temperatures. Soil fertility varies along a natural warming gradient from cold temperate to tropical and hot desert areas. In tropical systems, the air or shallow soil can reach 40–45 °C, while the upper threshold for fertility building is around 20–25 °C. Modeling shows that similar soil warming patterns exist in Asian, Southern African, and globally sensitive soil-climate configurations. Observations span various temporal and spatial scales, from decades to



millennia, across diverse regions. In Korea, soil heating and cooling paired with water retracement are significant, while waterlogged manure patches inhibit drying and warming elsewhere. First-order kinetic modeling reveals inter-continental and varying continental zones through substrate and vegetation factors. A framework captures soil-hydraulic features, warm-dry percolation, timing, and earthworm activity across different scales and structures. (M. Melillo et al., 2017)(Saïdou et al., 2009)

5.1. Field Studies in Temperate, Tropical, and Arid Systems

Studies on soil warming under elevated temperatures show that thermal gradients indicating ambient soil warming exist across various soil and climate types. These experiments demonstrate temperature slope responses aligned with established biogeochemical principles regarding temperature effects on soil fertility. Warming temperatures, between 2.7 and 11.6 °C, reflect historical non-anthropogenic periods. Research across temperate, tropical, and arid regions shows that soil carbon (C) stocks typically increase with ongoing temperature changes. Warm-adapted microbial communities emerge in substrates, soils, or litter, leading to significant turnover and agitation of upper soil layers. C accumulation potential often corresponds to existing soil C and seasonality but seems independent from easily digestible C availability, nutrient levels, or total microbial biomass. Very few links are evident for mitigating soil C loss in windy and hot conditions. Warming enhances early above-ground production while promoting C losses in high-latitude and arid-legume areas. In high-latitude tundra, warmer temperatures stimulate below-ground thaw and plant growth. Increased fungal and root biomass accompanies significant nitrogen (N) mineralization rises due to experimental warming in cold ecosystems. Minimal under-canopy litter accumulation occurs in unshaded tundra settings despite decades of variable precipitation. (M. Melillo et al., 2017)(Salazar et al., 2020)

5.2. Controlled Experiments and Temperature Manipulation

Controlled experiments manipulating soil temperature confirm and reinforce field observations on the beneficial role of temperature in the fertility of surface and subsurface soils. A summary of recent experiments underscores the diverse responses observed in vegetation and soil biogeochemical processes, specifically highlighting the favorable response of soil fertility indexes to elevated soil temperatures in several regions. A legislative consideration in the context of avoided warming emphasizes the urgent need to increase carbon storage in soils, notably in the Brazilian savannas (M. Ellison et al., 2019).



5.3. Modeling Approaches and Synthesis

Changes in soil temperature have been documented throughout much of the world in response to climate change (Liang, 2016). Short-term warming will affect soil microbiomes, influence nitrogen (N) transformation processes, increase continuous reflected light, and enhance organic carbon (C) decomposition, as observed from manipulative experiments and observational studies in surface soils. Fine-to-coarse texture ratios correlate with two diagenesis indices of N mineralization, highlighting processes governing the turnover in C and N between fine and coarse C. Changes in multilayer profiles in response to increased temperature should be further investigated. A mechanistic description of temperature and soil fertility, spanning over 50 years of climate-warming experiments, indicates that temperature and moisture levers influence biogeochemical cycles that control fertility and C sequestration. A model based on the observation that the effect of warming on C stock turnover varies significantly with climatic zones should be tested in tropical regions, where comprehensive observational data is lacking.

6. Implications for Agricultural Practice and Soil Management

Vegetative cover, residues, and organic amendments enhance soil thermal properties, sustain soil warmth, and improve fertility across diverse climates (S. A. Johnston et al., 2018). Soil management practices promoting warmer soils amplify cover-crop benefits and increase nutrient-water-temperature interplay, enhancing efficiency of inorganic nutrients and improving cropping system effectiveness. Cover crops, mulching, reduced tillage, and compost applications contribute positively to soil temperature (M. Melillo et al., 2017). Management fostering elevated soil temperatures across varied soils and environments delivers pro-fertility benefits, enabling crops to extract soil nutrients more efficiently throughout the season. Cover cropping, mulches, organic amendments, laser levelling for improved water infiltration, and inundation of paddy fields are agronomic strategies that positively influence soil temperature (Ozlu et al., 2022). Even low soil temperatures inhibit microbial activity, while higher temperatures stimulate activity and nutrient mineralization; improved soil management thus holds potential to optimise soil warmth and promote a more fertile environment.

Multiple peer-reviewed studies report significant soil-temperature variation across different cropping systems, with regional differences observed among diverse soils in South America, the United States, various provinces in China, and West Africa. Such observations indicate plentiful opportunities to enhance soil temperatures and improve



associated processes by optimising agronomic and cover-crop management within innumerable cropping systems on structurally diverse soils throughout the world.

7. Gaps in Knowledge and Future Research Directions

Many aspects of the relationship between temperature and soil fertility are poorly understood, emphasizing the need for focused research. Critical questions must be addressed regarding the mechanistic links between temperature and four fertility aspects. For example, how do rising temperatures influence soil evaporation and reduce hydraulic conductivity during desiccation? To what degree does increased coarse-fragment content impact soil-water matrix properties, thus affecting temperature and moisture retention? Additionally, which parameters notably influence these interactions, and how do they vary with climate and soil type? While biochemical processes related to weathering and organic-matter stabilization are well characterized, the role of temperature remains unclear. Temperature-fertility dynamics are also influenced by other environmental factors. Elevated CO₂ can enhance organic-matter decomposition and nutrient release, potentially offsetting moisture loss caused by rising temperatures. Conversely, increased volatility may hasten organic-matter depletion. Various minerals and organic substances interact with temperature, necessitating dynamic models that encapsulate multiple co-varying factors to evaluate changing multistressor environments. The focus on stable-equilibrium modeling may limit system understanding. Future research should investigate temperature-fertility interactions under warming scenarios and develop combined schemes for analysis. Practical questions regarding fertilization need addressing: when does maintaining fertility require temperature increases, and what strategies can raise fertility without modifying environmental factors? What adaptive management approaches can counteract temperature-fertility links?

8. Conclusion

A review of the relevant literature reveals no new insights since the last section on soil fertility, indicating a significant epistemic gap remains regarding its underlying mechanisms. However, current understanding warrants caution regarding assumptions about soil depth, climate class, and parent material related to fertilization. It cannot be assumed that any soil, mapped or not, or any climate or geological material, is inherently unworthy of fertilization if it has historically supported profitable crops. Mechanisms affecting soil fertility can still operate in conditions previously viewed as suboptimal. Changes in vegetation type or patterns due to temperature effects may lead to unexpected interactions. Thus, maintaining or restoring robust crop varieties offers a pathway to



enhance soil fertility through direct fertilization methods. Soils, climatic zones, parent materials, and crop types requiring post-fertilization stimulation deserve in-depth investigation. (Salazar et al., 2020)

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