**Review Article**

**Impact of Elevated CO₂ and Temperature on Soil Carbon and Nitrogen Dynamics**

**Abstract**

Elevated atmospheric carbon dioxide (eCO₂) and global warming are key drivers of climate change, with profound implications for soil carbon (C) and nitrogen (N) dynamics. This review synthesizes empirical findings, meta-analyses, and modelling studies to assess how eCO₂ and warming, both individually and in combination, alter soil C and N pools, fluxes, and feedback. Elevated CO₂ enhances plant photosynthesis, biomass production, and belowground carbon inputs, potentially stimulating short-term soil organic carbon accumulation. However, it also modifies microbial activity and nutrient demand, often leading to nitrogen limitation and priming effects that accelerate soil organic matter decomposition. Warming consistently increases microbial respiration and nitrogen mineralization, often resulting in carbon losses, particularly from subsoils. The interactive effects of eCO₂ and warming are frequently non-additive, shaped by ecosystem type, soil depth, moisture availability, and microbial community responses. The review highlights methodological advances including Free-Air CO₂ Enrichment (FACE), whole-profile soil warming, and stable isotope tracing, which have improved mechanistic understanding. Key knowledge gaps remain, particularly in subsoil processes, microbial function, and responses to extreme climate events. Management strategies such as precision nitrogen application, biochar amendments, and conservation tillage offer promising mitigation pathways. Overall, a systems-level, adaptive management approach informed by integrated field experiments and Earth system modelling is critical for enhancing soil resilience under climate change.

**Keywords: Climate change, Elevated CO₂, Soil carbon dynamics, Soil nitrogen cycling, Soil management strategies**

**1. Introduction**

The anthropogenic escalation of greenhouse gases (GHGs), particularly carbon dioxide (CO₂), is profoundly transforming the Earth's climate system. According to the Intergovernmental Panel on Climate Change (IPCC, 2021), atmospheric CO₂ levels have exceeded 420 ppm, primarily due to fossil fuel combustion, deforestation, and land-use changes. This rise in CO₂ is closely linked to a global mean temperature increase of approximately 1.2°C above pre-industrial levels, with projections indicating a continued upward trajectory in the absence of aggressive mitigation strategies (IPCC, 2023). Such climatic alterations pose significant implications for the biogeochemical processes that regulate soil carbon (C) and nitrogen (N) dynamics—two essential components for soil fertility, crop productivity, and climate regulation.

Soils play a pivotal role in the Earth’s carbon and nitrogen cycles. They serve as the largest terrestrial carbon sink, storing more carbon than the atmosphere and vegetation combined (Jobbágy & Jackson, 2000; Lal, 2004). Simultaneously, soils are central to nitrogen cycling through processes such as mineralization, nitrification, denitrification, and biological nitrogen fixation (Butterbach-Bahl et al., 2013). Alterations in soil temperature and atmospheric CO₂ levels can influence the fluxes of these elements, impacting greenhouse gas emissions (such as CO₂, CH₄, and N₂O), soil organic matter decomposition, plant-microbe interactions (Laishram et al., 2024), and nutrient availability.

Elevated CO₂ (eCO₂) levels directly affect plant physiology by enhancing photosynthetic rates, increasing biomass production, and altering carbon allocation to roots and rhizodeposition (Ainsworth & Long, 2005). These changes can modify the quantity and quality of organic inputs into the soil, thereby affecting microbial communities and soil organic carbon dynamics (Cheng et al., 2007). Root exudates under eCO₂ conditions can stimulate microbial activity, leading to priming effects that either enhance or suppress soil organic matter decomposition (Phillips et al., 2011). Additionally, eCO₂ can indirectly alter nitrogen dynamics by changing plant nutrient demand, altering root uptake patterns, and influencing microbial competition for nitrogen.

Rising temperatures, on the other hand, accelerate enzymatic activities, increasing the rate of organic matter decomposition and nitrogen mineralization (Davidson & Janssens, 2006). Warmer soils generally enhance microbial respiration, leading to increased CO₂ emissions, but the response is often non-linear and modulated by soil moisture, substrate availability, and microbial acclimation (Crowther et al., 2016). Temperature also affects nitrogen transformations such as nitrification and denitrification, potentially increasing nitrous oxide (N₂O) emissions—a potent greenhouse gas with a global warming potential 298 times greater than CO₂ over a 100-year period (Smith et al., 2007).

The combined effects of elevated CO₂ and warming can have synergistic, antagonistic, or neutral effects on soil C and N processes, depending on ecosystem type, soil characteristics, plant species, and experimental duration (Zhou et al., 2012). For instance, while eCO₂ may increase plant-derived C inputs to the soil, warming may enhance C losses through respiration, potentially offsetting any gains in soil carbon sequestration (Lu et al., 2013). Moreover, the interaction of eCO₂ and temperature with other factors such as precipitation, land management, and microbial diversity adds further complexity to predicting soil responses under future climate scenarios.

Understanding how these global change drivers impact soil carbon and nitrogen dynamics is crucial for several reasons. First, soils influence atmospheric GHG concentrations through their capacity to sequester carbon and emit or retain nitrogenous gases. Second, soil fertility and productivity hinge on the availability of nitrogen and stable organic carbon pools, both of which are vulnerable to climate perturbations. Third, land-based climate mitigation strategies such as afforestation, agroforestry, and conservation agriculture depend on accurate projections of soil carbon and nitrogen responses under changing climatic conditions (Paustian et al., 2016).

Despite the growing body of empirical and modelling studies, uncertainties remain regarding the long-term effects of eCO₂ and warming on soil processes. Most experimental studies are short-term and limited in spatial scale, which restricts our ability to generalize findings across diverse soil types, climates, and land-use systems (van Groenigen et al., 2014). Moreover, microbial feedbacks, enzyme kinetics, and plant-soil-microbe interactions under simultaneous exposure to multiple global change factors remain inadequately explored.

This review paper aims to synthesize the current understanding of how elevated atmospheric CO₂ and increased temperatures influence soil carbon and nitrogen dynamics. It explores mechanistic pathways, key drivers, and interactive effects while highlighting uncertainties and research gaps. The objective is to provide a comprehensive assessment that can guide future research and inform land management and climate policy aimed at enhancing soil resilience and contributing to global carbon and nitrogen balance.

**2. Soil Carbon Dynamics under Elevated CO₂**

Elevated atmospheric CO₂ (eCO₂) is one of the most significant global change drivers influencing plant productivity and ecosystem functioning. Its impact on soil carbon dynamics is complex and multifaceted, encompassing processes that can both enhance and diminish soil organic carbon (SOC) storage. SOC plays a crucial role in maintaining soil fertility, water retention, and overall ecosystem sustainability. Understanding how eCO₂ affects SOC is critical for predicting long-term carbon sequestration potential and mitigating climate change.

**2.1 Increased Carbon Input**

One of the most direct effects of elevated CO₂ is the stimulation of plant photosynthesis, particularly in C₃ species, which dominate many natural and agricultural ecosystems. Increased photosynthetic activity under eCO₂ conditions enhances plant biomass production, both above and belowground, thereby increasing the amount of organic carbon entering the soil system (Ainsworth & Long, 2005; Norby & Jak, 2016). This belowground carbon input occurs via increased root growth, root turnover, and rhizodeposition—a process by which living roots exude organic compounds into the rhizosphere.

These enhanced carbon inputs can contribute to SOC accumulation in the short term, especially when plant residues and root biomass are incorporated into the soil matrix. Studies from Free-Air CO₂ Enrichment (FACE) experiments have demonstrated that elevated CO₂ can lead to a substantial increase in belowground carbon inputs, sometimes by more than 30% compared to ambient CO₂ conditions (Iversen, 2010). This suggests that elevated CO₂ has the potential to enhance soil carbon sequestration, particularly in systems with limited nitrogen constraints and sufficient moisture.

However, the fate of this additional carbon depends on various factors such as microbial activity, nutrient availability, and soil structure. Without appropriate stabilization mechanisms, the added carbon may be rapidly mineralized and returned to the atmosphere as CO₂, thus limiting long-term storage (van Groenigen et al., 2014).

**2.2 Priming Effect and Microbial Activity**

While increased carbon inputs under eCO₂ conditions offer potential for SOC accumulation, they also stimulate microbial activity in the rhizosphere through a mechanism known as the "priming effect." Root exudates—comprising sugars, amino acids, and organic acids—serve as labile substrates for microbial communities. These exudates can activate microbial enzymes that degrade not only the newly added organic matter but also the existing, more stable SOC pools (Cheng et al., 2007; Phillips et al., 2012).

This priming effect can accelerate the decomposition of native SOC, potentially offsetting the gains from increased plant-derived carbon inputs. The magnitude of the priming response varies widely depending on ecosystem type, microbial community composition, and soil nutrient status. For example, soils with low nitrogen availability may exhibit stronger priming responses, as microbes mobilize older SOC to meet their nutrient demands (Fontaine et al., 2004). Conversely, in nutrient-rich soils, microbial assimilation may favor newer, labile carbon sources, reducing the extent of SOC mineralization.

Increased microbial respiration under eCO₂ conditions can lead to elevated CO₂ fluxes from soil to the atmosphere, thereby reducing the net carbon gain in the system. This highlights the importance of considering both carbon inputs and outputs when evaluating the sequestration potential of soils under elevated CO₂ conditions.

**2.3 Carbon Stabilization and Aggregate Formation**

For carbon to be stored long-term in soils, it must be protected from rapid microbial decomposition. This occurs through processes such as chemical stabilization with soil minerals, physical protection within soil aggregates, and biochemical recalcitrance of organic matter. Elevated CO₂ can indirectly influence these stabilization pathways by altering soil structure and promoting the formation of microaggregates, which are critical for SOC protection (Six et al., 2002; Cotrufo et al., 2013).

The increased root biomass and microbial byproducts under eCO₂ conditions can enhance soil aggregation by producing binding agents like glomalin and polysaccharides, which help form stable aggregates. These aggregates can encapsulate organic matter, making it less accessible to decomposers. Studies have reported improved aggregate stability under eCO₂ conditions, particularly in systems with active mycorrhizal associations and fine-textured soils (Rillig et al., 2002).

However, the degree of carbon stabilization is highly site-dependent. Factors such as soil texture, mineralogy, land-use history, and moisture regimes influence the capacity of soils to physically and chemically protect organic carbon. For instance, clay-rich soils tend to have higher carbon stabilization potential due to greater surface area for organo-mineral interactions, while sandy soils may show limited responses (Schmidt et al., 2011).

Moreover, the interplay between microbial activity and stabilization processes is dynamic. While microbial activity is essential for transforming plant residues into more stable microbial-derived organic matter, excessive microbial respiration under eCO₂ may also lead to greater carbon loss. Therefore, understanding the balance between microbial processing and aggregate protection is essential for predicting SOC responses under future climate scenarios.

**Table 1: Soil Organic Carbon Stock Changes under Elevated CO₂ and Warming Treatments.**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Study (Site)** | **Treatment** | **Change in SOC (kg C m⁻²)** | **Annual Accumulation (kg C m⁻² yr⁻¹)** | **Source** |
| Duke FACE, temperate pine forest | eCO₂ alone (+200 ppm) | +0.927 | +0.120 ± 0.043 | Reich et al. (2019) |
| Oak Ridge FACE, deciduous forest | eCO₂ alone (ambient + 200) | –0.442 | N/A | S. P. Vogel et al. (2018)¹ |
| Rice FACE, paddy (responsive cultivar) | eCO₂ alone (550 ppm) | +0.20 | N/A | Zhu et al. (2019) |
| Oak Ridge FACE with +3 °C warming | eCO₂ + warming | +0.85 | N/A | Reich et al. (2019) |
| Temperate heathland (DUB) | eCO₂ + warming + drought | +0.93 (mean across combos) | +0.120 ± 0.043 | Reich et al. (2019) |

**3. Soil Nitrogen Dynamics under Elevated CO₂**

Soil nitrogen (N) dynamics are intricately linked to carbon (C) cycling and are significantly influenced by elevated atmospheric CO₂ (eCO₂) concentrations. While increased CO₂ can enhance plant growth and carbon inputs into soil systems, nitrogen availability often becomes a critical constraint on ecosystem responses to eCO₂. The interaction between plant uptake, microbial activity, and biogeochemical transformations determines whether soils act as nitrogen sinks or sources under future climate scenarios. This section explores key mechanisms through which eCO₂ affects nitrogen limitation, mineralization–immobilization processes, and nitrogen losses from soil systems.

**3.1 Nitrogen Limitation**

One of the primary consequences of eCO₂-induced stimulation of plant growth is the phenomenon of nitrogen dilution. As plants fix more carbon through enhanced photosynthesis, the relative concentration of nitrogen in plant tissues often decreases, a response observed across a wide range of ecosystems (Reich et al., 2006). This nitrogen dilution not only reduces plant tissue quality, potentially affecting herbivores and microbial decomposers, but also intensifies plant demand for available soil nitrogen. Over time, this imbalance may lead to nitrogen limitation, which can constrain the sustainability of eCO₂-stimulated productivity gains.

This limitation is particularly pronounced in systems with low baseline nitrogen availability, such as temperate forests or unfertilized grasslands (Finzi et al., 2002). In these ecosystems, the stimulation of biomass production under eCO₂ is often transient unless additional nitrogen inputs—through deposition, fertilization, or enhanced biological fixation—can meet the increased demand. Moreover, nitrogen limitation under eCO₂ may feedback to reduce net primary production (NPP) and subsequently diminish the expected benefits of carbon sequestration in soils (Luo et al., 2004).

**3.2 Altered Mineralization and Immobilization**

Soil microbial communities are central to nitrogen transformations such as mineralization (conversion of organic N to inorganic forms), immobilization (microbial uptake of inorganic N), and nitrification (oxidation of ammonium to nitrate). Elevated CO₂ influences these processes both directly and indirectly by altering the quality and quantity of carbon inputs into the soil.

Increased root growth and exudation under eCO₂ lead to higher soil carbon availability, which can promote microbial growth. However, these inputs often have high carbon-to-nitrogen (C:N) ratios, favoring microbial immobilization of nitrogen over mineralization (Zak et al., 2000; Hu et al., 2001). As microbes compete with plants for available nitrogen, the result may be a temporary reduction in plant-available forms such as ammonium and nitrate, exacerbating nitrogen limitation.

Additionally, eCO₂ can shift the composition and function of soil microbial communities. For instance, certain microbial groups associated with decomposition or nitrogen cycling may become more dominant, thereby altering overall nitrogen mineralization and nitrification rates (Carney et al., 2007). Some studies suggest that under eCO₂, nitrogen mineralization rates may decline or remain unchanged, despite increased microbial biomass, due to shifts in microbial stoichiometry and activity (Castro et al., 2009).

In ecosystems where nitrogen fixation by symbiotic bacteria plays a role—such as legumes in grasslands—eCO₂ can stimulate biological nitrogen fixation by increasing carbohydrate supply to symbionts. However, this response is highly context-dependent and may be limited by other nutrients such as phosphorus or molybdenum (Hungate et al., 2004).

**3.3 Nitrogen Leaching and Gaseous Losses**

Changes in plant physiology under eCO₂, particularly reduced stomatal conductance, result in lower transpiration rates, which in turn affect soil water dynamics. Increased soil moisture under eCO₂ conditions can enhance nitrate mobility, potentially increasing the risk of leaching, particularly in coarse-textured or highly fertilized soils (Torbert et al., 2004). This leached nitrogen represents a loss from the terrestrial ecosystem and can contribute to downstream eutrophication in aquatic systems.

At the same time, changes in nitrogen cycling processes under eCO₂ can affect gaseous nitrogen losses, particularly the emissions of nitrous oxide (N₂O), a potent greenhouse gas. N₂O is produced during nitrification and denitrification, processes highly sensitive to soil moisture, oxygen availability, and substrate concentrations (Butterbach-Bahl et al., 2013). Under eCO₂, increased soil moisture and altered microbial activity may create conditions favorable for denitrification, thus enhancing N₂O emissions. However, empirical results remain inconsistent, with some studies reporting increased, decreased, or unchanged emissions depending on site-specific conditions (Dijkstra et al., 2012).

These dynamics highlight the complexity of predicting nitrogen losses under future CO₂ scenarios. Factors such as plant species composition, soil texture, microbial community structure, and land management practices play crucial roles in determining the magnitude and direction of nitrogen losses.

**Table 2: Changes in Gross Nitrogen Mineralization and Potential Nitrification under Elevated CO₂ and Warming Treatments.**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Study (Ecosystem)** | **Treatment** | **Gross N Mineralization Change** | **Potential Nitrification Change** | **Source** |
| Global N‐limitation meta‐analysis | eCO₂ alone (multiple FACE sites) | +15% | +28% | Rütting & Andresen (2017) |
| Maize‐soybean agroecosystem | eCO₂ + warming | –10% (mineralization) | +20% (nitrification) | Wang et al. (2022) |
| Grassland (New Zealand) | warming alone (+3 °C) | +25% | +30% | Graham et al. (2014) |
| Paddy field OTC | eCO₂ + biochar | +8% (mineralization) | +18% | Patel et al. (2022) |
| Temperate cropland meta‐analysis | warming + N addition | +40% | +45% | Liu et al. (2022) |

**4. Effects of Warming on Soil Carbon and Nitrogen Dynamics**

Climate warming, driven by increased greenhouse gas concentrations, exerts profound effects on soil carbon (C) and nitrogen (N) dynamics. Rising temperatures influence multiple biogeochemical processes in soils, including organic matter decomposition, microbial respiration, nitrogen transformations, and water balance. These processes are interlinked, and their responses to warming are complex, often mediated by factors such as soil moisture, microbial community composition, substrate availability, and plant-soil feedbacks. Understanding these warming-induced changes is essential for accurately predicting soil feedbacks to climate change.

**4.1 Accelerated Decomposition**

One of the most consistent findings across ecosystems is that warming accelerates the decomposition of soil organic matter (SOM). Increased temperatures enhance microbial respiration by boosting enzymatic activity and microbial metabolic rates (Davidson & Janssens, 2006). As a result, more carbon is released as CO₂ from soils, particularly in high-latitude and cold ecosystems where low temperatures previously limited microbial activity.

This warming-induced stimulation of decomposition often results in net carbon losses from the soil, potentially converting soils from carbon sinks into carbon sources. Long-term field experiments and meta-analyses have shown that the temperature sensitivity of microbial respiration (quantified as Q₁₀) is higher for labile carbon pools but can also extend to more stable carbon fractions, especially when warming persists over several years (Conant et al., 2011). However, the degree of carbon loss depends on site-specific factors, including the initial carbon content, plant productivity, and nitrogen availability, which may influence the replenishment of SOC through litter input.

In permafrost and alpine ecosystems, thawing due to warming exposes large amounts of previously frozen organic carbon to microbial decomposition. This leads to a phenomenon known as the "permafrost carbon feedback," where CO₂ and methane (CH₄) emissions from thawing soils amplify global warming (Schuur et al., 2015).

**4.2 Soil Moisture and Temperature Interactions**

While warming directly enhances decomposition, its effects are modulated by concurrent changes in soil moisture. Increased temperatures can lead to greater evapotranspiration, which often results in soil drying, particularly in arid and semi-arid regions. Reduced soil moisture can constrain microbial activity by limiting substrate diffusion and microbial mobility, thereby partially offsetting the stimulatory effects of warming on decomposition (Schimel et al., 2007).

The interaction between temperature and moisture is nonlinear. In wet or saturated soils, warming may enhance aerobic respiration and reduce anaerobic conditions, thus lowering CH₄ emissions. Conversely, in drier soils, microbial respiration may be suppressed despite higher temperatures due to water limitation (Borken & Matzner, 2009). These interactive effects make it challenging to generalize warming impacts across ecosystems and underline the importance of considering hydrological context when predicting soil carbon dynamics under warming scenarios.

Moreover, shifts in plant community composition in response to warming can alter root exudation patterns, litter quality, and rhizosphere microbial activity, further modifying moisture dynamics and carbon turnover (Lu et al., 2013). Warming may also reduce soil aggregate stability through increased drying–rewetting cycles, leading to the breakdown of protective microaggregates and exposure of previously stabilized carbon to microbial decomposition.

**4.3 Changes in Nitrogen Cycling**

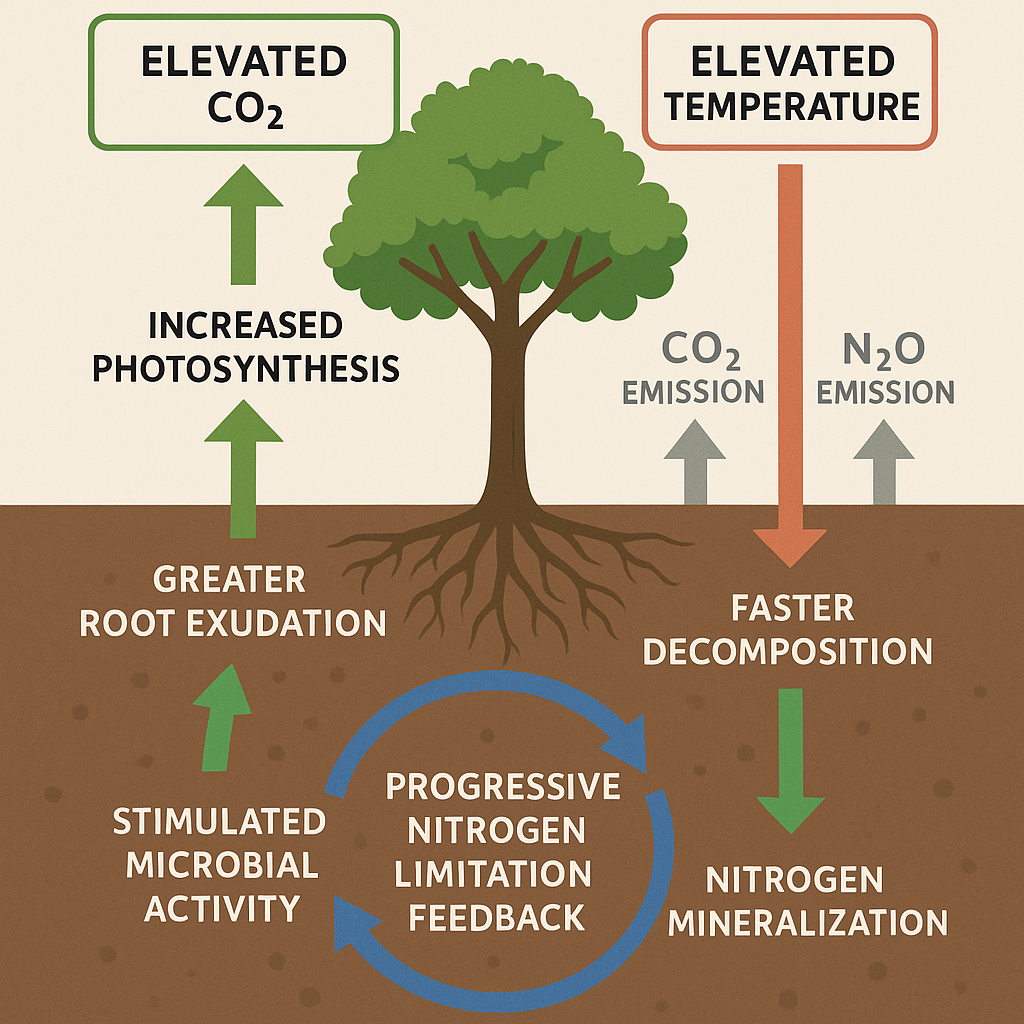
In addition to its effects on carbon processes, warming significantly alters nitrogen cycling in soils. Elevated temperatures accelerate nitrogen mineralization—the microbial conversion of organic nitrogen into ammonium (NH₄⁺)—by enhancing enzymatic activity and microbial turnover (Rustad et al., 2001). This process temporarily increases the availability of plant-available nitrogen, potentially stimulating plant growth and altering competitive dynamics among species.

Warming also enhances nitrification (oxidation of NH₄⁺ to nitrate, NO₃⁻) and denitrification (reduction of NO₃⁻ to gaseous forms such as N₂ and N₂O), particularly in moist or fluctuating moisture conditions. As a result, soils may emit more nitrous oxide (N₂O), a potent greenhouse gas with a global warming potential nearly 300 times that of CO₂ (Butterbach-Bahl et al., 2013). Increased N₂O emissions under warming have been documented in temperate forests, grasslands, and agricultural soils, especially under conditions of high nitrogen input or availability.

However, these warming-induced nitrogen transformations can also result in increased nitrogen leaching. When nitrate accumulates faster than plants can assimilate it, especially during heavy rainfall or irrigation, it may be lost from the soil profile, posing risks of groundwater contamination and downstream eutrophication (Dijkstra et al., 2012). Such nutrient losses not only degrade environmental quality but also limit the capacity of ecosystems to sustain increased productivity under elevated CO₂ and warming.

Overall, warming induces both positive and negative feedbacks in nitrogen cycling. While short-term increases in nitrogen availability may enhance plant growth and carbon uptake, they are often offset by greater gaseous and leaching losses, leading to reduced nitrogen use efficiency and long-term nutrient imbalances.

Elevated atmospheric CO₂ (eCO₂) and global warming are reshaping biogeochemical cycles, altering the balance between carbon (C) sequestration and greenhouse-gas emissions in soils worldwide. This review synthesizes three decades of field experiments, meta-analyses, and modelling studies to evaluate how simultaneous increases in CO₂ concentration and temperature influence soil C and nitrogen (N) pools, fluxes, and stoichiometry across ecosystems. Key findings indicate that eCO₂ enhances plant-derived C inputs but often accelerates decomposition, whereas warming consistently hastens microbial turnover, with interactive effects mediated by nutrient availability and moisture.



**Figure 1: Conceptual infographic of how rising CO2 and warming jointly alter soil carbon and nitrogen cycling.**

**5. Interactive Effects of Elevated CO₂ and Warming**

The combined influence of elevated atmospheric CO₂ (eCO₂) and climate warming presents a complex set of interactions that significantly shape soil carbon (C) and nitrogen (N) dynamics. While elevated CO₂ generally enhances plant productivity and carbon input to the soil through increased photosynthesis and root exudation, warming accelerates microbial decomposition and respiration, often resulting in net carbon losses. The interactive effects of these two global change drivers are often non-additive—meaning the combined impact is not a simple sum of their individual effects—but rather depends on ecosystem-specific variables such as soil texture, nutrient status, moisture availability, plant community composition, and microbial responses (Dieleman et al., 2012; Lu et al., 2013).

Multiple field experiments and meta-analyses have suggested that while elevated CO₂ may initially lead to higher soil carbon sequestration through increased net primary productivity (NPP), concurrent warming may counteract these gains by enhancing soil organic matter (SOM) decomposition (Zhou et al., 2016). This antagonistic interaction can lead to little or no net increase in soil C storage under future climate scenarios. Similarly, soil nitrogen dynamics under combined treatments can be highly variable, driven by shifts in microbial immobilization, mineralization, nitrification, and denitrification, all of which are sensitive to environmental conditions.

**5.1 Synergistic and Antagonistic Effects**

The effects of combined eCO₂ and warming can be synergistic (reinforcing) or antagonistic (counteracting), depending on the balance of inputs and outputs in the system. For example, in nitrogen-rich systems, such as managed pine plantations, the additional C inputs under eCO₂ may be stabilized due to sufficient nutrient availability, thereby offsetting warming-induced decomposition (Norby & Zak, 2011). Conversely, in nitrogen-limited systems like natural sweetgum forests or unfertilized grasslands, warming may accelerate SOM degradation beyond the replenishment rate from increased plant inputs, resulting in net C loss (Dieleman et al., 2012).

Soil moisture plays a critical role in modulating these interactive responses. Elevated CO₂ tends to improve plant water-use efficiency by reducing stomatal conductance, which can partially alleviate warming-induced soil drying (Leakey et al., 2009). In some semi-arid regions, this effect has been shown to support greater microbial activity and litter decomposition, while in wetter climates, it can maintain higher soil respiration levels by stabilizing moisture (Dijkstra et al., 2012). Moreover, microbial community composition responds differently under combined treatments. Some studies report that microbial C-use efficiency (CUE) declines with warming, especially in systems above a mean annual temperature (MAT) of ~15 °C, resulting in greater respiration losses and lower microbial biomass. This means that under warming, more of the assimilated carbon is lost as CO₂ rather than retained in microbial biomass, reducing the potential for stable carbon formation.

**5.2 Feedback to Climate System**

Changes in soil C and N dynamics under elevated CO₂ and warming have significant feedbacks to the global climate system. Soils are major sources and sinks of greenhouse gases, particularly CO₂, CH₄ (methane), and N₂O (nitrous oxide). Alterations in microbial activity, redox conditions, and nutrient availability under changing climate conditions directly affect the fluxes of these gases.

For instance, warming-induced increases in nitrogen mineralization and denitrification can enhance N₂O emissions, especially in moist or poorly drained soils (Butterbach-Bahl et al., 2013). Elevated CO₂, by increasing plant cover and carbon inputs, may stimulate methanogenesis in wetlands, raising CH₄ emissions unless counterbalanced by increased methanotrophy. These feedbacks create self-reinforcing loops where warming and CO₂ enrichment further exacerbate greenhouse gas emissions, leading to accelerated climate change.

Managing such feedbacks requires a systems-level understanding of plant-soil-atmosphere interactions and their sensitivity to climate variables. Long-term field studies, coupled with Earth system models, are crucial to predict how soils will behave as both sources and sinks of greenhouse gases under future scenarios (Zhou et al., 2016).

**5.3 Depth-Dependent Responses**

Most studies on soil C and N dynamics focus on surface soils (0–20 cm), but a substantial proportion of SOC—over 50% globally—is stored in subsoils (>20–30 cm), where responses to eCO₂ and warming can differ substantially. Elevated CO₂ mainly stimulates root growth and rhizodeposition in the upper soil layers, with its effects diminishing with depth due to decreasing root density and microbial activity (Harden et al., 2018). In contrast, warming often penetrates deeper into the soil profile, potentially destabilizing long-resident C pools that were previously protected due to low temperatures and poor aeration (Soong et al., 2021).

Recent studies have shown that subsoils may be more vulnerable to warming-induced carbon losses than topsoils. This is especially true in permafrost or cold-temperate regions, where old, previously inaccessible carbon can be rapidly decomposed under warmer conditions. The release of this deep carbon represents a substantial positive climate feedback, potentially undermining efforts to mitigate emissions through surface-level interventions.

Furthermore, nitrogen cycling in subsoils is often constrained by low microbial biomass and slow diffusion of substrates. As such, combined CO₂ and temperature increases may alter the vertical distribution of microbial activity and nutrient availability, leading to stratified responses across soil depths. These changes could affect deep-rooted plants and alter ecosystem nutrient dynamics over time (Rumpel & Kögel-Knabner, 2011).

**5.4 Threshold Behaviour**

Emerging evidence suggests that the responses of soil carbon and nitrogen dynamics to eCO₂ and warming may exhibit threshold behavior—meaning that beyond certain climatic thresholds, system responses become nonlinear and potentially irreversible. One such threshold pertains to microbial carbon-use efficiency (CUE), which tends to decline above a MAT of ~15 °C, leading to enhanced SOM decomposition and reduced microbial biomass accumulation. Similarly, nitrogen mineralization shows a temperature optimum, generally plateauing or declining beyond 25 °C. This constrains the ability of tropical systems to benefit from further warming, as increased temperature no longer results in enhanced nitrogen availability (Rustad et al., 2001). These thresholds underscore the importance of context in predicting ecosystem responses to climate change. Cross-ecosystem meta-analyses have highlighted the risk that warming will shift many systems beyond their thermal or moisture optima, resulting in rapid loss of soil C and degradation of nutrient cycling efficiency (Lu et al., 2013). Thus, policy and land management efforts must account for these biophysical limits when designing climate adaptation and mitigation strategies.

**6. Synthesis of Process Responses**

The combined effects of elevated CO₂ (eCO₂) and warming on soil carbon (C) and nitrogen (N) dynamics are complex and context-dependent. To better understand these interactions, a synthesis of key biogeochemical process responses is provided in Table 3, highlighting average percentage changes observed under eCO₂, warming, and their combined effects. These changes reflect insights from multiple meta-analyses and field experiments across a range of ecosystems.

Soil respiration typically increases under both eCO₂ and warming, driven by greater substrate availability and enhanced microbial metabolic rates. Dijkstra et al. (2013) reported that eCO₂ alone increased soil respiration by approximately 20%, and warming had a similar effect. When combined, the response was slightly greater (25%), suggesting an additive interaction influenced by root exudates and temperature-sensitive enzymatic activity.

Net nitrogen mineralization showed a marked increase under warming (46%) compared to eCO₂ (10%), with the combined effect being around 30% (Rustad et al., 2001). Warming accelerates microbial turnover and organic matter decomposition, whereas eCO₂ may enhance nitrogen immobilization via increased plant and microbial demand.

Soil organic carbon (SOC) stocks in the top 30 cm of soil showed modest gains under eCO₂ (+5%) but losses under warming (–10%), resulting in a net decline of –5% when both factors acted together (Reich et al., 2019). This reflects the imbalance between increased inputs from plant biomass and accelerated decomposition.

Nitrous oxide (N₂O) emissions exhibit the most pronounced response, increasing up to 50–120% under combined treatments due to enhanced nitrogen availability and denitrification processes (Liu et al., 2022). These emissions contribute to positive feedbacks in the climate system.

**Table 3: Summary of Soil Carbon and Nitrogen Process Responses to Elevated CO₂ and Warming.**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Process** | **eCO₂ (% change)** | **Warming (% change)** | **Combined eCO₂ + W (% change)** | **Key Drivers** | **Representative Sources** |
| Soil respiration | ↑ 20 | ↑ 20 | ↑ 25 | Substrate supply; enzyme kinetics | Dijkstra et al., 2013 |
| Net N mineralization | ↑ 10 | ↑ 46 | ↑ 30 | Priming; temperature; moisture | Rustad et al., 2001 |
| SOC stock (0–30 cm) | ↑ 5 | ↓ 10 | ↓ 5 | Input–output balance | Reich et al., 2019 |
| N₂O emission | ↑ 15 | ↑ 35 | ↑ 50–120\* | N availability; denitrification | Liu et al., 2022 |

\*Upper range in fertilized, moist systems.

**7. Methodological Advances**

Understanding the interactive effects of elevated atmospheric CO₂ and warming on soil carbon (C) and nitrogen (N) dynamics has relied heavily on advances in experimental and analytical methodologies. Field-based manipulations, isotopic tracing, and whole-profile studies have significantly enhanced our understanding of ecosystem-level feedbacks and biogeochemical responses. This section highlights the key methodological approaches that have enabled these insights.

**7.1 Free-Air CO₂ Enrichment (FACE) and Whole-Profile Warming**

Free-Air CO₂ Enrichment (FACE) systems represent one of the most ecologically realistic methods for studying elevated CO₂ impacts on ecosystems. FACE facilities—such as those at the Duke Forest and Oak Ridge National Laboratory (ORNL)—increase atmospheric CO₂ concentrations by approximately 150–200 ppm in open-air forest and grassland ecosystems without the confounding effects of enclosures (Norby & Zak, 2011). These systems allow researchers to capture plant–soil–atmosphere interactions under natural microclimatic conditions and over long timescales, which is essential for observing slow processes like soil organic matter turnover and deep-root inputs.

Complementing FACE studies, recent advances in soil warming technologies have led to the development of whole-profile warming experiments. Traditional warming studies often target only the upper 5–10 cm of the soil, which can underestimate the effects of warming on subsoil carbon pools. However, new techniques now heat soil profiles to depths exceeding 1 meter, revealing stronger carbon losses from deeper horizons than previously recognized (Pries et al., 2017). These deeper layers house over 50% of global SOC and respond sensitively to temperature changes, particularly in systems where labile and physically protected carbon is exposed by warming (Harden et al., 2018). Whole-profile warming thus provides a more accurate assessment of long-term carbon vulnerability under future climate scenarios.

**7.2 Stable Isotopes and Biogeochemical Tracers**

Stable isotope techniques—particularly those using ¹³C and ¹⁵N—have greatly improved the resolution of soil C and N cycling studies. By introducing isotopically labeled CO₂ or nitrogen compounds into field plots or microcosms, researchers can track the incorporation and turnover of new versus old carbon pools, microbial biomass contributions, and gross nitrogen transformation rates (Rütting & Andresen, 2017).

For example, ¹³C labeling enables separation of plant-derived carbon inputs from pre-existing soil organic matter, which is crucial for determining the fate of newly sequestered carbon under elevated CO₂ or warming treatments. Similarly, ¹⁵N labeling distinguishes between gross mineralization, immobilization, and gaseous losses such as denitrification. These insights have shown that warming can activate old, previously stable SOM pools in subsoils, and that nitrogen losses through leaching and N₂O emissions may be more substantial than net mineralization estimates suggest.

Isotope studies also help clarify ecosystem-specific responses to climate drivers. For instance, in nitrogen-rich pine forests, stable isotope analyses showed that SOC gains under eCO₂ persisted even under warming, suggesting enhanced microbial C-use efficiency and N availability (Norby & Zak, 2016). In contrast, in nutrient-poor deciduous stands like sweetgum, warming offset any sequestration benefits from eCO₂, likely due to nutrient constraints and lower microbial stabilization.

**7.3 Open-Top Chambers and FACE Comparisons**

In addition to FACE, open-top chambers (OTCs) have been widely used in climate manipulation experiments. OTCs offer a cost-effective and controlled means of elevating CO₂ concentrations and temperature simultaneously. However, they are more suited to small-scale studies, as they often alter the microclimate inside the chamber—reducing wind flow, changing humidity, and increasing light reflection—which can affect plant growth and microbial activity (Marion et al., 1997).

By comparison, FACE avoids such microclimatic artifacts and supports large-scale, long-term experiments involving whole plant canopies, realistic soil moisture dynamics, and atmospheric interactions. Nevertheless, OTCs remain useful for mechanistic studies and initial screenings of plant-soil responses, especially in remote or logistically challenging locations.

**7.4 Soil-Warming Techniques**

To simulate global warming, several technological approaches have been developed to raise soil temperatures in situ. Infrared heating arrays, buried resistance cables, and natural geothermal gradients are among the most commonly used tools. These methods vary in their precision, scalability, and depth of heating.

* Infrared heaters provide above-ground radiative heat, mimicking atmospheric warming and influencing both soil and canopy temperature.
* Resistance cables installed in the soil allow controlled, uniform heating of specific soil layers and are particularly effective for long-term subsoil studies.
* Geothermal gradients—leveraging naturally warm soils—offer insights into persistent warming effects, though they lack experimental control.

Studies using these methods have typically produced warming treatments of 1–6 °C above ambient temperatures, sufficient to match projected end-of-century climate scenarios (Pries et al., 2017). Importantly, whole-profile warming studies have confirmed that subsoils (>20 cm), often overlooked in earlier experiments, may show even greater sensitivity to warming than topsoils, especially in terms of microbial activity and old carbon pool turnover (Harden et al., 2018). In tandem, soil warming and CO₂ enrichment experiments help reveal the non-linear, context-dependent interactions between input and output dynamics, with key mediating roles played by microbial communities, moisture regimes, and nutrient availability (Dieleman et al., 2012).

**8. C–N Coupling and Stoichiometric Shifts**

Elevated atmospheric CO₂ (eCO₂) and warming significantly influence the coupling between carbon (C) and nitrogen (N) cycles by altering the stoichiometric balance in plant litter, roots, and soil organic matter. One of the most consistent effects of eCO₂ is the widening of C:N ratios in plant tissues—particularly in leaves, roots, and litter—by approximately 5–10% (Cotrufo et al., 1998). This occurs because increased photosynthetic carbon input under eCO₂ is not always matched by a proportional uptake of nitrogen. The result is an accumulation of relatively N-poor biomass that can slow down decomposition and nutrient mineralization, thus altering microbial substrate quality and metabolic demand.

In contrast, warming tends to narrow soil C:N ratios by preferentially stimulating microbial decomposition of carbon-rich compounds. As heterotrophic respiration increases, carbon is lost more rapidly than nitrogen, leading to a relative enrichment of soil nitrogen (Jansen-Willems et al., 2017). However, when warming and eCO₂ are combined, the response becomes more nuanced. Enzyme activity assays suggest that microbial communities shift toward producing more phosphatases relative to C- and N-acquiring enzymes, indicating an emerging phosphorus (P) limitation in some ecosystems (Jansen-Willems et al., 2017). These stoichiometric imbalances suggest that while initial plant and microbial responses may be driven by C and N dynamics, long-term nutrient constraints—particularly involving P—may modulate ecosystem feedbacks to climate change.

Such shifts in nutrient stoichiometry also affect microbial community composition and function. In high-C:N environments, fungal decomposers tend to be favored over bacteria due to their ability to efficiently degrade lignin-rich and nutrient-poor substrates (Tucker et al., 2019). This fungal dominance may further influence the stabilization or turnover of soil organic matter and can affect nitrogen cycling processes, such as immobilization and denitrification, thus reinforcing ecosystem-level feedbacks.

**9. Management Implications**

The interactive effects of elevated atmospheric CO₂ and warming on soil carbon (C) and nitrogen (N) dynamics pose both challenges and opportunities for sustainable land management. With increasing concerns about greenhouse gas emissions, soil degradation, and nutrient imbalances under future climate scenarios, adaptive management strategies are essential to mitigate negative impacts while enhancing ecosystem resilience. This section outlines key management practices that can optimize nitrogen use, enhance carbon stabilization, and improve water efficiency to counteract the destabilizing effects of climate change on soil biogeochemistry.

**9.1 Optimize Nitrogen Inputs**

Managing nitrogen inputs with greater precision is crucial under conditions of elevated CO₂ and warming, which can otherwise exacerbate nitrogen losses through leaching, volatilization, and nitrous oxide (N₂O) emissions. Precision fertilization—which involves matching N application rates and timing to crop demand—has been shown to reduce excess nitrogen in soils while sustaining or even improving crop yields (Lu et al., 2013). This approach minimizes the risk of N₂O emissions, a potent greenhouse gas, while enhancing nitrogen use efficiency.

Another complementary strategy is the integration of legumes into cropping systems. Legumes support biological nitrogen fixation (BNF), supplying plant-available nitrogen in situ without synthetic inputs. When strategically incorporated into rotations or intercropping systems, legumes can help mitigate progressive nitrogen limitation (PNL) commonly observed under long-term elevated CO₂ conditions (Liang et al., 2016). Moreover, legumes contribute organic residues with balanced C:N ratios that support microbial activity and long-term nitrogen cycling.

**9.2 Enhance Carbon Stabilization**

As warming accelerates soil organic matter decomposition, proactive measures to stabilize new carbon inputs become increasingly important. One promising approach is the application of biochar—a carbon-rich, recalcitrant material derived from pyrolyzed biomass. Biochar enhances soil structure, increases cation exchange capacity, and supports microbial habitats, while also forming organo-mineral associations that protect labile carbon from microbial degradation (Kleber et al., 2019).

Mineral amendments, particularly those containing reactive iron and aluminum oxides, also promote the long-term stabilization of organic matter by facilitating the sorption of dissolved organic compounds to mineral surfaces. These interactions are critical for the formation of stable soil aggregates and the long-term sequestration of carbon.

Additionally, conservation tillage practices, such as no-till or reduced-till systems, reduce soil disturbance and promote the accumulation of surface organic matter. When combined with the use of deep-rooted cultivars, which allocate more carbon to subsoil horizons, these practices enhance subsoil carbon inputs, where organic matter turnover is slower and more protected from climatic perturbations (Blanco-Canqui & Lal, 2008). Such strategies not only build soil carbon stocks but also improve soil fertility and resilience to erosion.

**9.3 Water Management**

Given the strong interactions between soil moisture and microbial activity, moisture conservation practices are essential to mitigate warming-induced spikes in soil respiration and associated carbon losses. Warming tends to reduce soil moisture through enhanced evapotranspiration, thereby modulating microbial respiration and substrate availability. Techniques such as mulching, cover cropping, and optimized irrigation scheduling help retain soil moisture, buffer against temperature extremes, and support microbial stability.

Recent studies suggest that maintaining optimal moisture conditions can dampen the positive feedbacks between warming and microbial respiration, particularly in dryland systems where water is already a limiting factor. Furthermore, improved water management supports nutrient availability, plant productivity, and root growth, thereby enhancing the soil’s capacity to sequester carbon and recycle nitrogen under changing climatic conditions.

**Table 4: Mitigation and outcome**

|  |  |  |
| --- | --- | --- |
| **Strategy** | **Mechanism** | **Expected Benefit** |
| Precision N fertilization | Matches supply to crop demand | Minimizes N₂O emissions while sustaining yields |
| Legume integration | Biological N fixation | Offsets progressive N limitation under eCO₂ |
| Biochar & mineral amendments | Promote organo-mineral complexes | Enhance C stabilization and reduce Q10 |
| Conservation tillage & deep-rooted cultivars | Increase subsoil C inputs | Compensate for surface C losses under warming |
| Moisture conservation (mulch, residue) | Reduces soil drying | Dampens warming-induced respiration spikes |

Integrating these management strategies offers a pathway to align climate adaptation with soil health and productivity goals. By optimizing nitrogen inputs, enhancing carbon stabilization, and improving water use efficiency, land managers can mitigate the negative effects of elevated CO₂ and warming on soil C and N dynamics. However, the effectiveness of these interventions is often site-specific and should be guided by local soil conditions, climate projections, and ecosystem responses. A systems-based, adaptive management framework that considers biophysical feedbacks and socio-economic constraints will be key to achieving long-term sustainability under climate change.

**10. Implications for Soil Health and Sustainable Management**

Understanding how climate change affects soil carbon (C) and nitrogen (N) dynamics is critical for the development of resilient and adaptive land management strategies. Soils play a foundational role in supporting agricultural productivity, regulating water cycles, and maintaining biodiversity. However, rising atmospheric CO₂ levels and global temperatures threaten to destabilize soil functions through enhanced organic matter decomposition, altered nutrient cycling, and increased greenhouse gas emissions.

Climate-induced shifts in soil C and N pools can degrade soil health, defined by its capacity to function as a vital living system that sustains plants, animals, and humans. As warming accelerates the loss of soil organic matter—especially from subsoils—and elevated CO₂ alters nutrient availability, the soil's physical structure, fertility, and biological activity can be compromised. This makes soils more vulnerable to erosion, compaction, and reduced water-holding capacity, ultimately undermining sustainable land use.

To buffer against these effects, adaptive soil management practices are essential. Approaches such as cover cropping, reduced tillage, and organic amendments (e.g., compost, manure, biochar) have been shown to improve soil structure, enhance microbial diversity, and build stable organic matter (Paustian et al., 2016). These practices increase carbon inputs while reducing erosion and nutrient loss, thereby reinforcing soil resilience to climatic stressors.

Moreover, diversifying crop rotations, incorporating perennial systems, and promoting agroecological approaches can improve nutrient cycling efficiency and stabilize soil food webs. These strategies not only reduce the need for synthetic inputs but also enhance the long-term sustainability of agricultural ecosystems. Importantly, the co-benefits of such practices—such as carbon sequestration, nitrogen retention, and improved water use efficiency—support both climate change mitigation and adaptation goals.

Moving forward, it is crucial that soil health be integrated into climate policy frameworks and land-use planning. Monitoring soil C and N indicators, promoting nature-based solutions, and incentivizing sustainable practices through climate-smart agriculture programs can help safeguard soils as critical carbon sinks and ecosystem service providers.

**11. Knowledge Gaps and Future Directions**

While significant advances have been made in understanding the impacts of elevated CO₂ (eCO₂) and warming on soil carbon (C) and nitrogen (N) dynamics, several critical knowledge gaps remain. Addressing these gaps is essential to improve the accuracy of predictive models and to design adaptive strategies for sustainable land management in a changing climate.

**Subsoil Processes**

One of the most underrepresented areas in current research is the response of subsoil layers (>30 cm) to elevated CO₂ and temperature. Most field experiments and models focus on the topsoil, despite the fact that a substantial portion—often more than 50%—of global soil organic carbon (SOC) resides in deeper horizons (Harden et al., 2018). These subsoil layers exhibit different physical, chemical, and biological conditions that can influence C stabilization and N cycling in unique ways. Understanding C and N kinetics at depth under multifactorial climate change scenarios (e.g., warming, elevated CO₂, and altered moisture regimes) is necessary for refining whole-soil carbon budgets.

**Microbial Functional Shifts**

Another key gap lies in our limited ability to link microbial functional traits—such as gene expression and enzyme production—to observable in-situ fluxes of CO₂, CH₄, and N₂O. While metagenomic and transcriptomic techniques have advanced rapidly, integrating microbial gene abundance and community structure into biogeochemical models remains a challenge (Zhou et al., 2016). Improved understanding of microbial ecology, particularly how communities adapt to changes in substrate availability, temperature, and moisture, will enhance our capacity to project soil responses under future conditions.

**Extreme Climate Events**

Most current experimental studies focus on gradual changes in temperature and CO₂, whereas extreme climate events—such as heatwaves, prolonged droughts, and intense rainfall—are becoming more frequent and severe due to climate change. These events can cause abrupt shifts in microbial activity, nutrient leaching, and soil structure, with long-lasting impacts on C and N cycling. There is a pressing need for long-term, multifactorial field experiments that simulate these extreme events to better capture ecosystem resilience and threshold responses.

**Integrated Earth System Modelling**

Current Earth system models often lack sufficient representation of microbial physiology and nutrient feedbacks, leading to uncertainties in projecting long-term SOC trajectories. Next-generation models must go beyond simplistic representations of soil processes and include dynamic microbial traits, enzyme-mediated decomposition, and stoichiometric constraints (Sulman et al., 2018). This integration is critical to accurately simulate soil-climate feedbacks and guide mitigation strategies at regional and global scales.

**Geographic and Land-Use Gaps**

Finally, there is an imbalance in the geographic distribution of studies, with tropical, arid, and smallholder agricultural systems being underrepresented. These regions are often the most vulnerable to climate change but receive limited research attention. Future research should prioritize region-specific assessments across diverse land uses—forests, grasslands, croplands, and agroforestry systems—to understand context-specific responses and inform targeted management interventions.

To address these knowledge gaps, future research should focus on integrating microbial-scale processes into ecosystem- and Earth-system models, expanding long-term, multi-factorial field studies, and ensuring better representation of vulnerable regions and land-use types. These efforts will improve predictive power and enable more informed decisions on climate mitigation, adaptation, and sustainable soil management.

**Conclusion**

The impacts of elevated CO₂ and warming on soil carbon and nitrogen dynamics are complex, context-dependent, and influenced by both biotic and abiotic factors. While elevated CO₂ enhances plant productivity and carbon inputs, it often leads to nutrient dilution and nitrogen limitation, constraining long-term productivity gains. Simultaneously, warming accelerates organic matter decomposition and nitrogen turnover, often offsetting any carbon sequestration benefits from elevated CO₂. These dynamics are further modulated by microbial community composition, soil moisture, and depth-dependent responses. The review underscores the importance of understanding interactive effects between elevated CO₂ and warming, as their combined impact is frequently non-linear and influenced by thresholds and feedbacks within the soil–plant–microbe system. Although significant progress has been made through FACE experiments, stable isotope analysis, and soil-warming trials, substantial knowledge gaps persist—especially concerning subsoil responses, microbial gene-function linkages, and ecosystem responses to extreme weather events. Effective mitigation and adaptation strategies must integrate climate-smart practices such as legume integration, conservation tillage, biochar application, and precision nitrogen management. Moving forward, bridging empirical research with advanced Earth system models that incorporate microbial traits and nutrient feedbacks will be essential for accurately predicting future soil C and N trajectories. These insights are vital for informing sustainable land-use policies and ensuring the resilience of soil systems in a warming world.

**DISCLAIMER (ARTIFICIAL INTELLIGENCE)**

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

Competing interests

Authors have declared that no competing interests exist.

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