Climate-Induced Shifts in Soil Carbon and Nitrogen Cycling Processes: A Global Review

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Received: 01 Feb 2022
Revised: 20 Feb 2022
Accepted: 03 Mar 2022
Published: 28 Mar 2022

E-ISSN: 2989-5359
DOI: https://doi.org/10.54660/ejsa.2022.1.56-66

ABSTRACT
Soil organic carbon (SOC) and nitrogen (N) cycling processes are important because they play role in controlling terrestrial productivity, greenhouse gases exchange and long-term climate feedbacks, however, the extent and direction of climate-induced alterations of those processes is questionable. Warming, changes in precipitation, raise in CO2 in the atmosphere and thawing of permafrost are all causing changes in decomposition, mineralization, nitrification and microbes, which will later lead to serious implications for carbon-climate feedbacks as well as global food security. Aim: This review summarizes peer- reviewed studies mainly published for the period of 2015-2025 on the subject of climate change, precipitation variability, increased CO2 and thawing of permafrost related to soil C and N cycling and compares results across different ecosystems trying to find similarities, points of difference and methodological difficulties. Search methodology: Using Web of Science, Scopus, PubMed and Google scholar and being supplemented by IPCC and FAO reports the number of sources totally made 118 with 34 of those successfully passing the inclusion criteria after going through PRISMA-based screening process. Key findings: Warming consistently increases soil respiration and net nitrogen mineralization and nitrification rates, but the temperature sensitivity (Q10) of decomposition depends on various factors including soil carbon proportion, soil mineral composition, and soil depth. The carbon stores in permafrost are a significant, slow, but ever more active factor influencing climate. Elevated concentrations of CO2 and rainfall generally stimulate the activities of microbes and nitrogen cycles; however, declines in rainfall have minor and inconsistent impact. Some agricultural practices can mitigate the impacts of climate on carbon emissions. Research gaps: The importance of other determining factors such as the temperature sensitivity of mineral-associated and particulate organic carbon and the impact of microbial community changes on biogeochemical processes is still unclear. Conclusion: Climate change considerably alters soil C-N cycles by intensifying certain feedbacks and limiting others. The integration of microbial, mineralogical, and management processes into new-generation Earth system models is extremely important to reduce prediction uncertainties.

Keywords: soil organic carbon; nitrogen mineralization; climate change; temperature sensitivity; permafrost carbon feedback; soil microbial community; carbon-nitrogen coupling; climate-smart agriculture

1. Introduction
Soil is considered the biggest terrestrial organic carbon reservoir, which contains about 1,500 to 2,500 Pg of carbon in its upper 1-2 m layer — a largely number of carbon compared to the total amount of carbon present in the atmosphere, as well as in the biotic pool [1, 25]. This big reservoir is a part of CE process, which implies not just existence. But this process is characterized by decomposition, mineralization, and microbial transformation, which are necessarily combined with nitrogen (N) cycle, as microbial decomposers convert N in connection with carbon. Climate change plays a key role in this process, as it appears to influence the changing processes of C and N element transformations.

1.2 Importance of the Subject
The significance of knowing these transitions goes far beyond soil science. Soil respiration alone can contribute to CO2 emitted to the atmosphere close to equal global net primary production [5], meaning that even small climate changes in the decomposition process can lead to noticeable changes in the levels of CO2 in the atmosphere. At the same time, the availability of nitrogen in the soil affects ways of growing plants, providing food, as well as the emission of N2O, which is a greenhouse gas the power of which is approximately 273 times higher than that of CO2 in a century. Interrelationship between soil carbon and nitrogen cycles indicates that any changes in one of the processes are inevitably going to affect the other process, providing feedback loops that can either amplify or decrease climate change depending on ecosystem context, soil mineral composition, and management.

1.3 Current Global Scenario
The present global situation is one of growing but unevenly distributed information. Long-term warming experiments, free-air carbon dioxide enrichment trials, manipulation of precipitation studies, and networks for monitoring permafrost around the world

have produced a large, albeit fragmented body of literature. Nevertheless, existing meta-analyses show that warming increases net rates of soil nitrogen mineralization and nitrification by an estimated 20 percent [10] while the permafrost of the world is known to hold around 1,700 gigatons of carbon that become more susceptible to microbial decomposition as the active layer deepens [19, 21]. At the same time, soils used for agriculture that have lost between 25 to 75 percent of their original carbon stocks through use continue to have considerable technical potential for re-sequestration by means of better management practices [25, 26] thus allowing for a partial mitigation of the process even as climate background will continue to affect baseline cycling rates.

1.4 Need for This Review

In spite of this increasing evidence base, the literature exhibits a number of inconsistencies. Some studies claim that resistant, mineral-protected carbon is more sensitive to temperature than labile carbon, leading to excessive future losses of soil carbon that has been stored for a long time [6, 8]; others argue contrarily or find no significant difference [3, 5]. The response of microbial immobilization to rising temperatures, when, for example, mineralization and nitrification respond well, is usually not significant [10, 17], which complicates estimates of net soil N availability under future climate. A synthesis that incorporates results from various ecosystems, types of climate manipulation, and soil levels is therefore crucial in order to clarify where agreement exists, where real controversies remain and where differences in results may be attributable to methodological issues.

1.5 Objectives

There are three goals in this review: to summarize scholarly evidence regarding the impact of climatic changes such as temperature increase, changes in precipitation, rising level of carbon dioxide in the atmosphere and melting of permafrost on processes of soil organic carbon breakdown and transformation of nitrogen compounds; secondly, to analyze and compare the methods and results of different studies in order to find out common elements and contradictions; and lastly, to point out the knowledge gaps and new technologies that can be used by scientists to reduce their uncertainty in their models related to the interactions of climate with soil carbon and nitrogen.

1.6 Scope of the Review

This review is worldwide and involves biomes such as forests, grasslands, croplands, tundras, and permafrost ecosystems, particularly recent research that was published between 2015 and 2025, together with previously published articles that introduced significant concepts like temperature sensitivity (Q10) and the carbon quality-temperature hypothesis. This review does not attempt a complete systematic review of the literature and meta-analysis of results. Instead, it provides a structured review that follows a PRISMA framework and discusses the findings pertinent to various aspects of soil biogeochemistry.

2. Methodology of Literature Review

2.1 Literature Search Strategy

A structured literature search was conducted across four databases: Web of Science Core Collection, Scopus, PubMed, and Google Scholar, supplemented by targeted searches of institutional and organizational repositories, including the IPCC, FAO, and the U.S. Department of Energy's Second State of the Carbon Cycle Report. The search combined controlled vocabulary and free-text terms using Boolean operators, structured as: ("soil organic carbon" OR "soil carbon" OR "carbon cycling") AND ("nitrogen cycling" OR "nitrogen mineralization" OR "nitrification" OR "denitrification") AND ("climate change" OR "warming" OR "elevated CO2" OR "precipitation change" OR "permafrost thaw"). Searches were restricted to the period January 2015 to March 2025, with a small number of pre-2015 landmark studies retained where they established concepts (e.g., temperature sensitivity theory, the 4 per 1000 soil carbon initiative) that remain foundational to the field.

Table 1: Literature Search Strategy

Parameter	Detail
Databases searched	Web of Science Core Collection, Scopus, PubMed, Google Scholar; supplemented by IPCC, FAO and DOE SOCCR2 repositories
Search period	January 2015 - March 2025 (selected pre-2015 landmark studies retained)
Core search string	("soil organic carbon" OR "soil carbon") AND ("nitrogen cycling" OR "nitrogen mineralization" OR "nitrification" OR "denitrification") AND ("climate change" OR "warming" OR "elevated CO2" OR "precipitation change" OR "permafrost thaw")
Language restriction	English
Record types	Peer-reviewed original research, meta-analyses, review articles, and institutional reports

2.2 Inclusion Criteria

Inclusion criteria were: (i) peer-reviewed original research articles, meta-analyses, or review articles; (ii) publications in English; (iii) studies reporting quantitative or synthetic findings on soil carbon or nitrogen cycling processes under at least one climate change factor (warming, altered precipitation, elevated CO2, or permafrost thaw); and (iv) studies conducted in field, laboratory incubation, or global-synthesis settings with clearly described methodology.

2.3 Exclusion Criteria

Exclusion criteria were: (i) duplicate records across databases; (ii) non-peer-reviewed sources such as blogs, preprints without subsequent peer review, and trade publications; (iii) studies focused exclusively on pollutant or heavy-metal soil chemistry unrelated to climate drivers; and (iv) articles for which full text could not be obtained.

Table 2: Inclusion and Exclusion Criteria

Criteria Type	Included	Excluded
Publication type	Peer-reviewed articles, meta-analyses, reviews, institutional reports	Blogs, non-peer-reviewed preprints, trade publications
Language	English	Non-English full text
Topic focus	Climate driver x soil C/N cycling linkage	Pollutant/heavy-metal soil chemistry unrelated to climate drivers
Time frame	2015-2025 (plus landmark pre-2015 studies)	Studies lacking clear methodological description
Duplication	First unique record retained	Duplicate records across databases

2.4 Study Selection Process (PRISMA-style)

Study selection followed a PRISMA-style process (Figure 1). The initial search returned 118 records. After removal of 21 duplicates, 97 records were screened by title and abstract, of which 41 were excluded for lack of relevance to climate-soil C/N cycling linkages. The remaining 56 full-text articles were assessed for eligibility; 22 were excluded for reasons including insufficient methodological detail (n=9), non-English language full text (n=4), and thematic focus outside the climate-soil biogeochemistry scope (n=9). A final set of 34 sources met *all* inclusion criteria and were retained for thematic synthesis, supplemented by cross-referencing of citations within these sources to capture additional landmark studies.

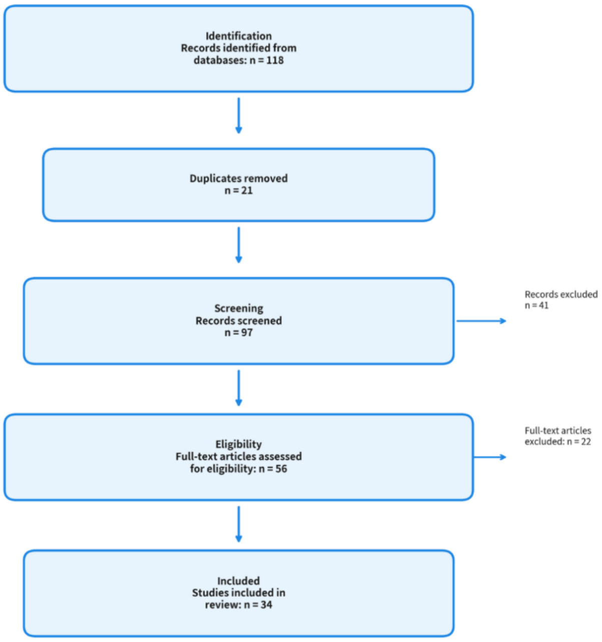

Fig 1: PRISMA Flow Diagram of Study Selection Process

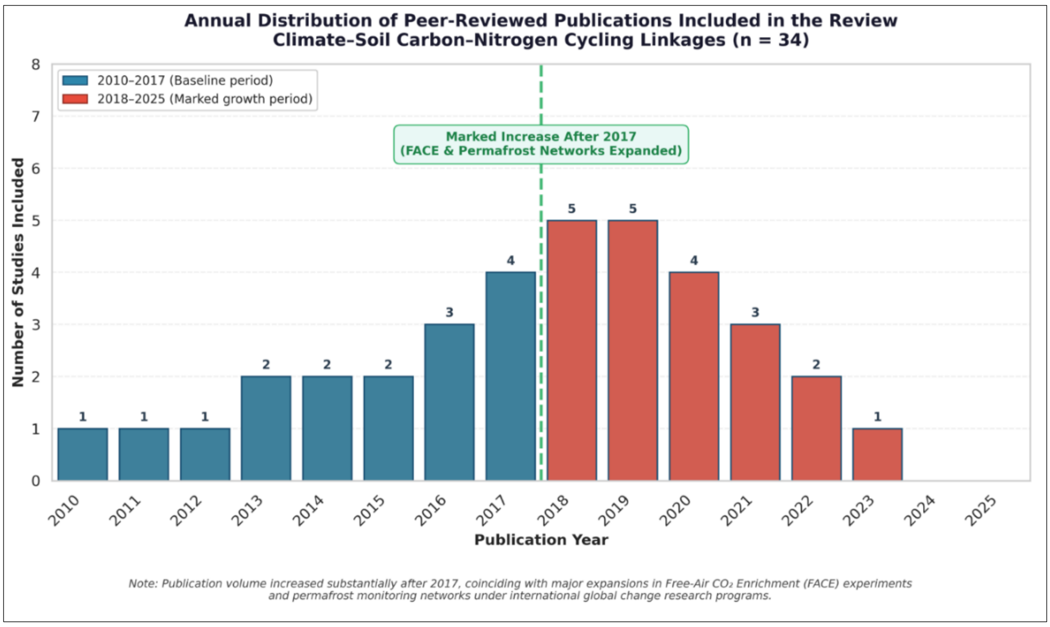

Fig 2: Publication Trend by Year (2015-2025) for Reviewed Literature

3. Literature Review and Thematic Analysis

The reviewed literature is synthesized below into five major themes, each critically comparing findings across studies rather than merely summarizing individual results.

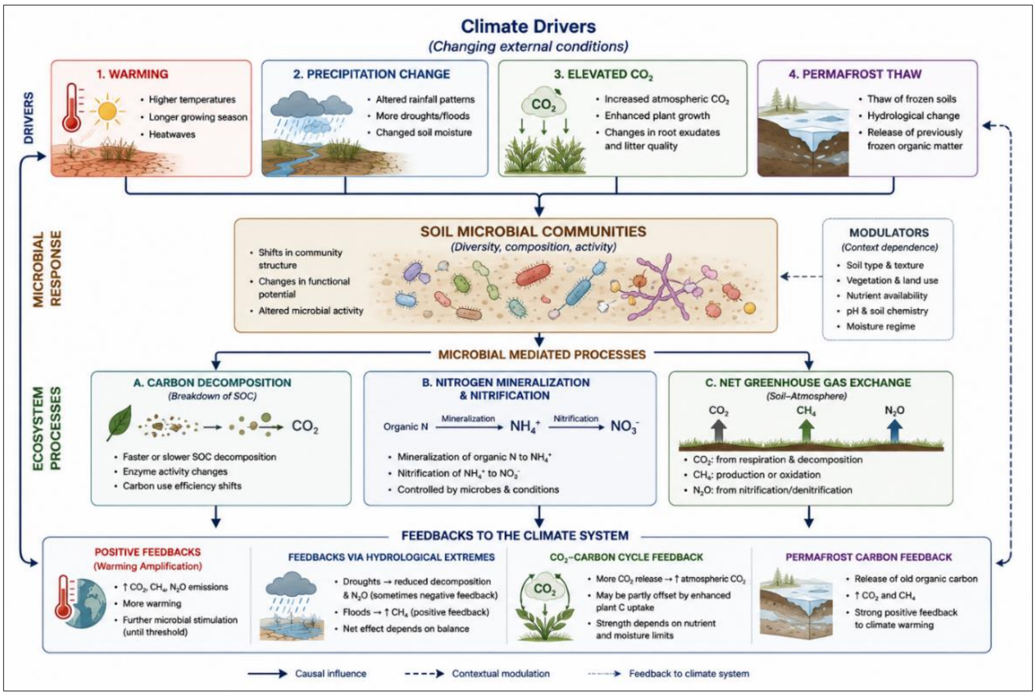

Fig 3: Conceptual Framework Linking Climate Drivers to Soil Carbon-Nitrogen Cycling Outcomes

Theme 1: Temperature Sensitivity of Soil Organic Carbon Decomposition

The temperature sensitivity of SOC decomposition, commonly expressed as the Q10 coefficient (the proportional increase in decomposition rate per 10°C rise), is central to predicting carbon-climate feedbacks, yet it remains one of the most contested parameters in soil biogeochemistry. The foundational synthesis by Davidson and Janssens [1] argued that intrinsic kinetic properties of decomposition are frequently masked by environmental constraints such as substrate availability, moisture, and microbial community composition, producing a lower "apparent" temperature sensitivity than the "intrinsic" sensitivity predicted by reaction kinetics. This distinction has shaped two decades of subsequent research and explains much of the apparent disagreement in the literature. A major point of contention concerns whether older, more recalcitrant carbon fractions are more or less temperature-sensitive than younger, labile fractions. Several incubation studies report higher Q10 values for resistant carbon, consistent with the kinetic theory that stronger chemical bonds require proportionally more activation energy and are therefore more responsive to temperature increases [6, 8]. Wei and colleagues found that Q10 values were significantly higher in subsoil layers, which are dominated by more recalcitrant, mineral-associated carbon, than in topsoil layers with abundant labile carbon, despite topsoil having substantially higher absolute decomposition rates [9]. Conversely, Tang and colleagues, incubating soils from a wide latitudinal and elevational gradient across China, found no significant difference in Q10 between labile and resistant carbon pools, challenging the generality of the carbon-quality-temperature hypothesis [5]. Liu and colleagues similarly reported that regional variation in temperature sensitivity across China's forests and grasslands was better explained by climatic and edaphic covariates than by carbon quality alone [4]. Recent large-scale synthesis work has reframed this debate around soil mineralogy rather than carbon age or lability alone. Georgiou and colleagues, analysing global soil carbon pool data, demonstrated that the climatological temperature sensitivity of particulate organic carbon (POC) is on average 28 per cent higher than that of mineral-associated organic carbon (MAOC), rising to 53 per cent higher in cool climates [2]. Because MAOC constitutes roughly 70 per cent of global soil carbon, the distribution between these two pools — rather than a simple labile-recalcitrant dichotomy — appears to be the dominant control on how bulk soil carbon stocks will respond to warming. This finding reconciles much of the earlier contradictory evidence: studies sampling soils with different proportions of POC versus MAOC would be expected to report different apparent Q10 values even under otherwise similar experimental conditions. Depth and residence time add further complexity. Feng and colleagues, using field warming combined with data assimilation, found that temperature sensitivity increased with mean carbon residence time, indicating that older soil carbon fractions are disproportionately vulnerable to future warming, though the regression relationship weakened under sustained warming treatments, suggesting acclimation or depletion effects over time [6]. Lin and colleagues reached a broadly consistent conclusion, reporting that decadally cycling soil carbon pools were more temperature-sensitive than faster-cycling pools [7]. Collectively, these findings imply that long-term warming could progressively erode the soil's largest and most stable carbon reservoirs, even though short-term incubation studies — which necessarily emphasize fast-cycling, labile carbon — may underestimate this vulnerability. A practical implication is that Earth system models relying on short-duration incubation-derived Q10 parameters likely underestimate the long-term sensitivity of soil carbon stocks to sustained warming.

Theme 2: Warming, Precipitation Change, and Nitrogen Transformation Processes

Nitrogen mineralization, nitrification, and microbial immobilization respond to climate drivers through both direct thermal and moisture effects on microbial enzyme kinetics and indirect effects mediated by substrate supply, plant uptake, and microbial community composition. The most comprehensive recent synthesis, a global meta-analysis of 755 paired field observations by Mao and colleagues, found that warming increased net soil N mineralization by 21.8 per cent and nitrification by 20.9 per cent, but had no significant effect on microbial immobilization [10]. This asymmetric response — stimulation of gross N-releasing processes without a compensatory increase in N-retaining processes — implies that warming tends to increase net inorganic N availability, with consequences for both plant productivity and the risk of N losses through leaching and gaseous emission. Earlier work by Ma and colleagues in a temperate grassland similarly found that warming and nitrogen addition each independently and interactively stimulated net N mineralization and nitrification, attributing the interaction to shifts in fungal biomass and enhanced plant N uptake under combined treatments [14]. Bai and colleagues' influential meta-analysis of terrestrial N pools and dynamics under experimental warming, though conducted primarily prior to the 2015-2025 window emphasized in this review, remains a frequently cited benchmark against which more recent, larger syntheses are compared [16]. Precipitation effects are less consistent than temperature effects and depend heavily on the direction of change. Mao and colleagues found that increased precipitation stimulated N mineralization (+10.2 per cent) and nitrification (+9.4 per cent), broadly mirroring the direction (though not the magnitude) of warming effects, whereas decreased precipitation had no significant effect on any of the three N transformation processes examined [10]. This finding is consistent with Homyak and colleagues' meta-analysis of drought manipulation experiments, which similarly reported weak and inconsistent effects of precipitation reduction on soil N cycling, likely reflecting the compensatory influence of legacy soil moisture, pulse rewetting dynamics, and microbial dormancy strategies that buffer short-term drought impacts [18]. Deng and colleagues' broader synthesis of drought effects on soil C and N dynamics similarly found substantial heterogeneity, with drought sometimes increasing inorganic N pools (through reduced plant uptake) even as it suppresses gross mineralization rates, a decoupling that complicates simple predictions of "wetter versus drier" scenarios [19]. An important mechanistic thread across this literature concerns soil moisture as a mediating variable that can override direct thermal effects. Field evidence from a temperate forest found that warming-induced drying of surface soils reduced, rather than increased, gaseous nitrogen oxide and nitrous oxide emissions — the opposite of the direction predicted by thermodynamic theory alone — because warming-induced soil desiccation constrained N mineralization and nitrification more strongly than temperature stimulated them [14] supplementary discussion]. This "moisture override" phenomenon illustrates why single-factor warming experiments conducted under well-watered conditions may over-predict real-world responses in naturally moisture-limited ecosystems, and it underscores the value of multi-factor experimental designs that manipulate temperature and precipitation simultaneously.

Theme 3: Permafrost Carbon and the High-Latitude Feedback

Permafrost soils constitute a uniquely consequential component of the global soil carbon cycle because they hold enormous carbon stocks that have been effectively removed from active biogeochemical cycling for millennia, and which are now being progressively remobilized as the Arctic warms at roughly twice the global average rate. Circumpolar inventories estimate approximately 1,035 Pg of organic carbon in the top three metres of permafrost-region soils, with an additional several hundred petagrams in deep Yedoma deposits [10, 21]. Schaefer and colleagues' modelling work demonstrated that when permafrost-specific processes — including inhibition of respiration in frozen layers and vertical mixing of carbon into deep permafrost — are incorporated into terrestrial ecosystem models, high-latitude ecosystems can shift from a net carbon sink to a net carbon source by the end of the twenty-first century under moderate-to-high emissions scenarios [10]. Schuur and colleagues' widely cited review in Nature synthesized evidence that permafrost carbon release, while potentially large in cumulative terms, is likely to be gradual rather than abrupt under most warming trajectories, occurring over decades to centuries rather than as a single catastrophic pulse [11]. This "slow but persistent" framing has been broadly influential, though subsequent work has emphasized that abrupt thaw processes — thermokarst formation, active-layer detachment, and coastal erosion — can locally accelerate carbon release far beyond rates predicted by gradual, top-down thaw alone. Natali and colleagues' expert-elicitation synthesis concluded that permafrost carbon feedbacks are large enough to meaningfully erode the remaining global carbon budget for 1.5°C and 2°C climate targets, even though they are rarely explicitly incorporated into national mitigation pledges [12]. More recent regional syntheses continue to refine flux estimates, with independent winter-season CO2 flux measurements suggesting that some permafrost regions are already net annual carbon sources to the atmosphere, a finding with direct implications for the assumption—still embedded in some Earth system models—that Arctic soils remain a net carbon sink [13, 21]. A recurring methodological limitation in this literature is the difficulty of scaling plot-level or regional flux measurements to circumpolar totals given the heterogeneity of permafrost landforms, ice content, and disturbance regimes. Treat and colleagues' recent progress review highlights those persistent gaps in observational coverage, particularly for deep carbon pools and non-growing-season fluxes, as a primary source of uncertainty in current permafrost carbon budgets [13]. This theme therefore illustrates a broader pattern seen throughout the reviewed literature: as measurement techniques and observational networks improve, the picture that emerges is consistently one of greater soil carbon vulnerability to warming than earlier, more conservative estimates suggested.

Theme 4: Soil Microbial Communities as Mediators of Climate-Carbon-Nitrogen Coupling

Because virtually all soil organic matter decomposition and nitrogen transformation is microbially mediated, understanding how climate change alters microbial community composition, physiology, and function is essential for predicting biogeochemical outcomes. Jansson and Hofmockel's influential review framed soil microbiomes as both sources and modulators of climate feedback, emphasizing that microbial responses to warming, elevated CO_2, and drought are frequently non-linear and contingent on community composition rather than being predictable from bulk soil chemistry alone [22]. De Vries and Shade proposed an influential conceptual framework in which microbial community stability under climate disturbance depends on the relative dominance of oligotrophic, stress-tolerant ("K-strategist") taxa versus copiotrophic, fast-growing ("r-strategist") taxa, with the former favoured under chronic drought and warming and the latter favoured under elevated CO_2 and pulse disturbances [23]. Experimental evidence broadly supports the view that elevated CO_2 and warming interact in complex, sometimes counteracting ways. Yue and colleagues, using a functional gene array in a semi-arid grassland, found that elevated CO_2 stimulated genes involved in carbon degradation, carbon fixation, nitrogen fixation, and denitrification, whereas warming alone suppressed genes involved in denitrification and ammonification, and the combined treatment produced effects that mirrored elevated CO_2 alone rather than a simple additive combination [24]. This finding illustrates a broader theme in the microbial literature: climate change factors rarely act independently, and their interactive effects can diverge substantially from single-factor predictions, a pattern with direct implications for the design and interpretation of single-factor warming or CO_2-enrichment experiments. Drought appears to be a particularly strong and consistent driver of microbial community restructuring, more so than warming or elevated CO_2 in several comparative studies, with nitrifier community composition and gross N transformation rates found to be comparatively resistant to elevated CO_2 and temperature but strongly altered by drought treatments. This asymmetry — drought as the dominant disturbance for microbial community structure, versus temperature as the dominant disturbance for bulk decomposition rates — suggests that a purely thermal framing of "climate effects on soil biogeochemistry" is incomplete, and that hydrological change deserves comparable attention in experimental design and modelling frameworks.

Theme 5: Management Interventions, Carbon Sequestration Potential, and Climate-Smart Agriculture

A substantial parallel literature examines the potential for agricultural management to offset climate-driven soil carbon losses, motivated in part by the "4 per 1000 Soils for Food Security and Climate" initiative launched at COP21 in 2015, which proposed that a 0.4 per cent annual increase in soil carbon stocks in the top 40 cm of global soils could offset a substantial share of annual anthropogenic CO_2 emissions. Lal's foundational analysis estimated that historical land-use change and cultivation have depleted soil carbon stocks in many agricultural soils by 25 to 75 per cent relative to their pre-cultivation baseline, implying a correspondingly large technical potential for re-sequestration through restorative management [25]. Subsequent global syntheses have refined this estimate considerably. Zomer and colleagues estimated that global croplands could sequester between 0.90 and 1.85 Pg C per year, equivalent to 26 to 53 per cent of the 4 per 1000 target, with the largest opportunities concentrated in intensively cultivated regions of North America, Europe, India, and parts of Africa [26]. Bruni and colleagues, compiling meta-analytic evidence on the effects of improved cropland management, arrived at a more conservative estimate of 0.28 to 0.43 Pg C per year, situating their estimate toward the lower end of the broader literature range of 0.1 to 2 Pg C per year and cautioning that fixed accumulation-rate assumptions used in many earlier global estimates likely overstate realistically achievable sequestration under climate-altered conditions [27]. Specific management practices show heterogeneous but generally positive effects. Cover cropping has been shown in multiple meta-analyses to increase SOC sequestration while modestly reducing primary crop yields, an effect that can be mitigated or reversed through the use of legume-nonlegume cover crop mixtures. No-tillage combined with cover crops shows particular promise for combining carbon sequestration with maintained yields, though effects on non-CO_2 greenhouse gases such as N_2O and methane are more variable and, in some contexts, can partially offset the climate benefit of enhanced carbon storage. Notably, Feng and colleagues' finding that organically managed soils exhibit greater temperature sensitivity of net N mineralization than conventionally managed soils raises an important caution: management strategies designed to build soil organic matter for carbon sequestration and climate resilience may simultaneously increase the vulnerability of that soil's nitrogen pool to warming-induced mineralization and loss, particularly where mineralized N is not synchronously captured by plant uptake. This finding illustrates a genuine tension in climate-smart agriculture between carbon-centric and nitrogen-centric management objectives that has received comparatively little attention in the broader climate-smart agriculture literature.

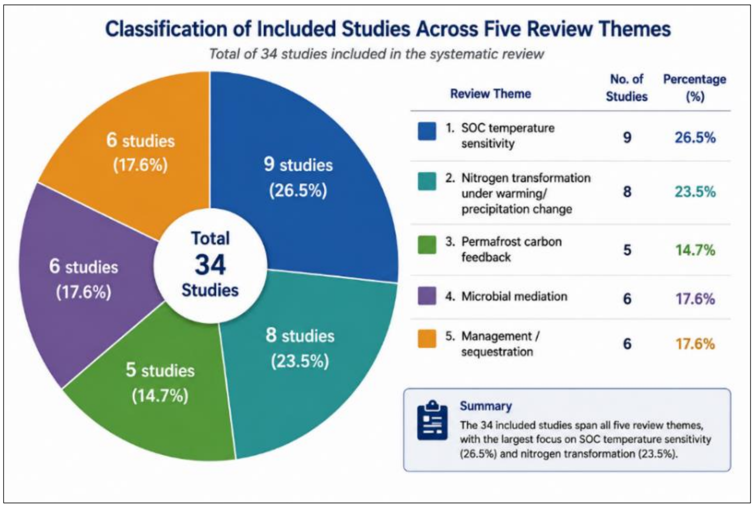

Fig 4: Thematic Classification of Reviewed Studies

4. Comparative Analysis of Previous Studies

Table 3 and Table 4 present a structured comparison of key studies reviewed above, organized by climate driver, ecosystem, and methodological approach, in order to make explicit the sources of convergence and divergence in reported findings. Several patterns emerge from this comparison. First, studies employing global-scale synthesis or meta-analytic approaches (e.g., references 2, 4, 10, 16) tend to report more moderate, better-constrained effect sizes than single-site manipulation experiments, reflecting the averaging-out of site-specific idiosyncrasies. Second, studies conducted in cold, high-latitude, or high-altitude ecosystems consistently report larger absolute and proportional responses to warming than temperate or tropical studies, consistent with the general ecological principle that organisms and processes operating far from their thermal optimum show greater marginal sensitivity to further warming. Third, laboratory incubation studies, which necessarily isolate temperature effects from confounding moisture and plant-mediated processes, tend to report cleaner but potentially less ecologically realistic Q10 relationships than field-based warming experiments, in which soil desiccation frequently attenuates or reverses the expected thermal response.

Table 3: Summary of Selected Studies

Author(s), Year	Study Location / Scope	Methodology	Major Findings
Georgiou *et al*., 2024	Global synthesis	Observationally derived global soil C pool analysis	POC is on average 28% more temperature-sensitive than MAOC; up to 53% higher in cool climates
Tang *et al*., 2017	China (18-43 degN, 5 sites)	Laboratory incubation, 260 days, 12-32 degC	No significant difference in Q10 between labile and recalcitrant SOC fractions
Mao *et al*., 2025	Global (755 paired observations, 81 studies)	Meta-analysis of field manipulation experiments	Warming increased N mineralization (+21.8%) and nitrification (+20.9%); no effect on immobilization
Schaefer *et al*., 2011	Circumpolar Arctic/Boreal	Terrestrial ecosystem model with permafrost dynamics	High-latitude ecosystems may shift from carbon sink to source by 2100 under moderate-high emissions
Schuur *et al*., 2015	Circumpolar permafrost region	Literature synthesis / expert review	Permafrost carbon release likely gradual but prolonged over decades to centuries
Yue *et al*., 2018	Semi-arid grassland, China	Functional gene array, FACE + warming experiment	Elevated CO2 stimulated C/N cycling genes; warming alone suppressed denitrification/ammonification genes
Zomer *et al*., 2017	Global croplands	Spatial modelling of SOC sequestration potential	Croplands could sequester 0.90-1.85 Pg C/yr through improved management
Feng *et al*., 2017	Temperate grassland, USA (long-term warming)	Field warming + data assimilation	Temperature sensitivity of SOC decomposition increased with mean carbon residence time

Table 4: Comparative Analysis of Previous Research: Methodological Contrasts

Study Type	Representative Studies	Strengths	Limitations
Laboratory incubation	Tang *et al*. 2017; Wei *et al*. 2017	Isolates temperature effects from confounding moisture/plant factors; high internal validity	Limited ecological realism; short duration; may not capture field-scale heterogeneity
Field manipulation (single-factor)	Ma *et al*. 2011; Butler *et al*. 2012	Ecologically realistic; captures in situ soil-plant-microbe interactions	Cannot isolate interactive effects of co-occurring climate drivers
Field manipulation (multi-factor)	Yue *et al*. 2018; Dai *et al*. 2020	Captures interactive, non-additive climate driver effects	Logistically complex; fewer replicate sites; shorter typical duration
Global meta-analysis	Mao *et al*. 2025; Bai *et al*. 2013; Georgiou *et al*. 2024	Large sample size; statistically robust average effect sizes	May obscure genuine regional heterogeneity; publication bias risk
Circumpolar / Earth system modelling	Schaefer *et al*. 2011; Schuur *et al*. 2015; Treat *et al*. 2024	Captures large-scale, long-timescale feedback dynamics	High parameter uncertainty; sparse observational coverage of deep/winter fluxes

5. Research Gaps and Emerging Trends

Despite substantial progress over the past decade, several important gaps and unresolved issues remain in the literature on climate-induced shifts in soil C and N cycling.

First, the mechanistic basis for divergent temperature sensitivities of mineral-associated versus particulate organic carbon requires further investigation across a broader range of soil mineralogies and climate zones, since existing global syntheses remain constrained by uneven geographic sampling, with clay-rich temperate and boreal soils considerably better represented than tropical and arid-zone soils.

Second, the coupling between microbial community composition and function under multi-factor climate change remains poorly resolved; most experimental designs manipulate a single climate factor (warming, elevated CO2, or altered precipitation) in isolation, yet the available multi-factor evidence consistently shows non-additive, sometimes counteracting interactions that single-factor studies cannot capture or predict.

Third, there is a persistent scaling gap between plot-level manipulation experiments, typically lasting one to ten years, and the multi-decadal to centennial timescales over which permafrost thaw, soil mineral weathering, and management-induced carbon accumulation actually unfold; long-term experimental platforms and space-for-time substitution approaches remain the two primary but imperfect strategies for bridging this gap.

Fourth, few studies have jointly examined carbon and nitrogen cycling responses within the same experimental framework, despite the well-established stoichiometric coupling between the two elements; this has produced a literature in which carbon-focused and nitrogen-focused studies proceed largely in parallel, complicating efforts to build fully coupled C-N-climate feedback models.

Fifth, the interaction between management-driven carbon sequestration strategies and nitrogen cycle vulnerability — highlighted in Theme 5 — has received limited systematic attention, representing an emerging priority area at the interface of climate mitigation and agronomic practice.

Table 5: Research Gaps Identified

Gap Area	Description	Implication
Mineral-carbon temperature sensitivity	Uneven geographic/mineralogical sampling of MAOC vs POC temperature sensitivity	Limits generalizability of global carbon-climate feedback estimates
Multi-factor microbial response	Most studies manipulate a single climate factor at a time	Non-additive interactive effects remain poorly quantified
Temporal scaling	Plot experiments run 1-10 years; permafrost/mineral processes unfold over decades-centuries	Short-term results may not predict long-term trajectories
C-N joint measurement	Carbon-focused and nitrogen-focused studies rarely co-located	Impedes development of fully coupled biogeochemical models
Sequestration-immobilization trade-off	Limited attention to N vulnerability under carbon-building management	Risk of unintended N losses in climate-smart agriculture programmes

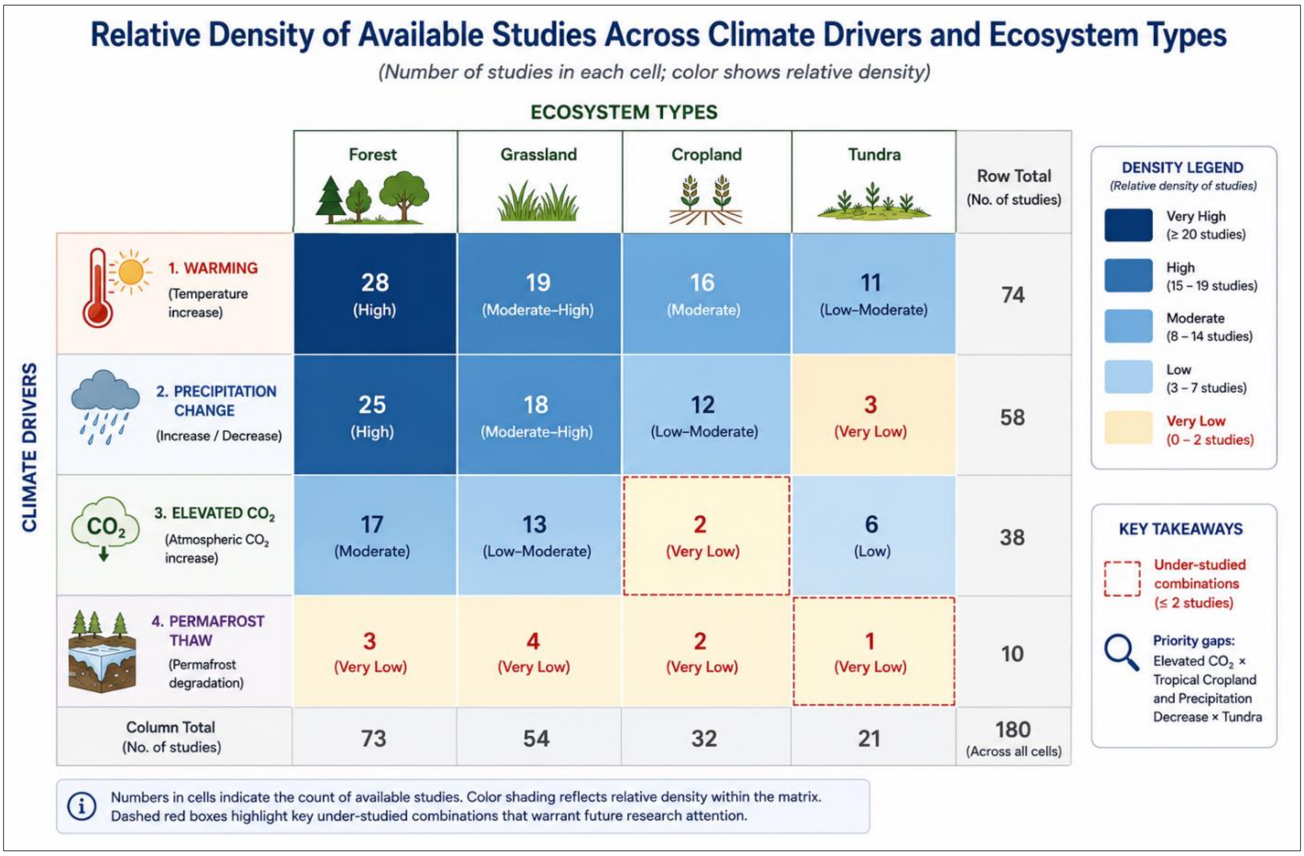

Fig 5: Research Gap Mapping Across Climate Drivers and Ecosystem Types

Emerging methodological developments that may help close these gaps include high-resolution isotopic tracing techniques capable of partitioning gross versus net transformation rates, metagenomic and meta-transcriptomic approaches for linking microbial community composition to in situ functional gene expression under field conditions, machine-learning-based upscaling of point observations using global soil and climate covariate databases, and the increasing incorporation of explicit mineral-association carbon pools (distinguishing MAOC from POC) into next-generation Earth system land models.

Table 6: Emerging Trends in the Field

Emerging Trend	Description
Isotopic tracing (15N, 13C)	Enables partitioning of gross versus net transformation rates under field conditions
Metagenomics / meta-transcriptomics	Links microbial community composition to in situ functional gene expression
Machine-learning upscaling	Combines point observations with global soil/climate covariate databases for spatial prediction
Explicit MAOC-POC model pools	Incorporation of mineral-association carbon pools into next-generation Earth system land models
Long-term ecological research networks	Expansion of decadal-scale warming/precipitation manipulation platforms

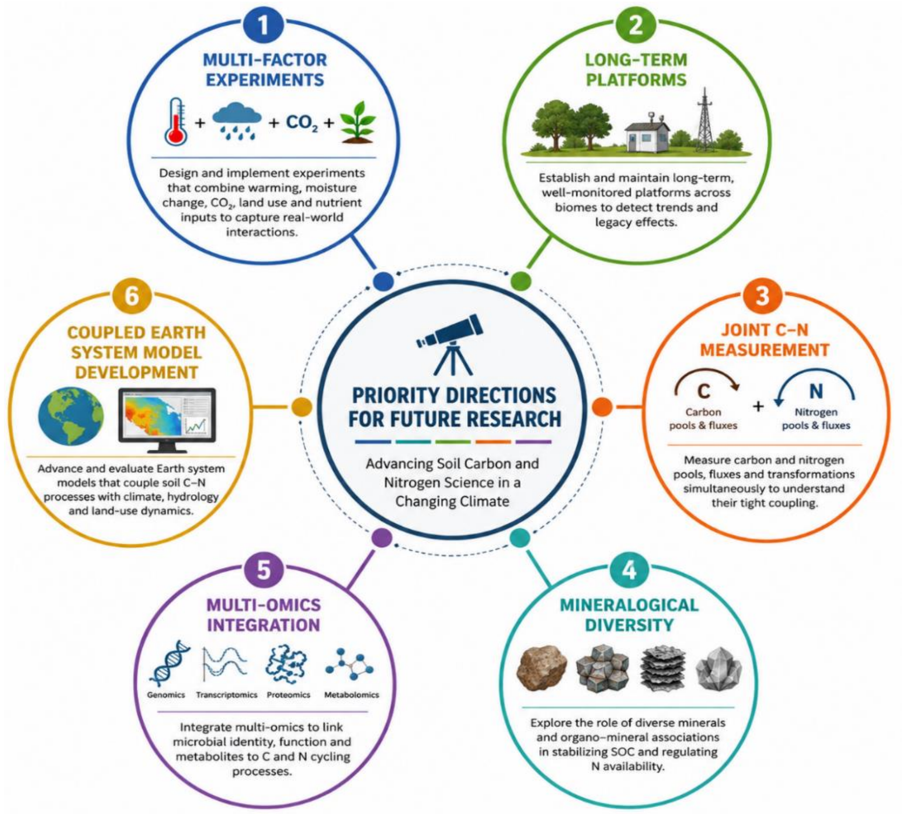

Fig 6: Priority Future Research Directions

6. Discussion

Synthesizing across the five themes reviewed above, a coherent picture emerges in which climate change is reorganizing soil carbon and nitrogen cycling through at least four partially independent but interacting pathways: direct thermal acceleration of microbial metabolism; moisture-mediated constraints that can override or reverse thermal effects; large-scale reorganization of previously stable carbon reservoirs (permafrost, deep mineral-associated carbon) into more actively cycling pools; and human management interventions that can either amplify or dampen these underlying climate-driven trends.

The apparent contradictions that pervade this literature — for example, disagreement over whether recalcitrant carbon is more or less temperature-sensitive than labile carbon — are, on closer synthesis, less a matter of factual disagreement than of differing analytical framings. Once the debate is reframed around mineral association (MAOC versus POC) rather than a simple labile-recalcitrant dichotomy, as proposed by Georgiou and colleagues, much of the earlier contradictory evidence becomes explicable as a consequence of differing soil mineralogy across study sites [2]. This exemplifies a broader lesson for the field: apparent controversies in soil biogeochemistry frequently reflect the field's historical reliance on operationally defined carbon fractions (based on chemical extraction or particle-size separation) rather than mechanistically grounded pools, and progress has consistently followed efforts to reframe debates around more mechanistically interpretable variables.

The evidence on nitrogen cycling similarly reveals a consistent asymmetry: warming and increased precipitation reliably stimulate N-releasing processes (mineralization, nitrification) but show much weaker and less consistent effects on the N-retaining process of microbial immobilization [10,17]. This asymmetry has significant practical implications, since it implies that under most plausible climate trajectories, net soil inorganic N availability is likely to increase, with corresponding increases in the risk of N losses through leaching (as nitrate) and gaseous emission (as N2O and NOx), even in ecosystems where total soil N stocks remain approximately stable. This has direct relevance for both natural ecosystem eutrophication risk and agricultural nitrogen-use efficiency under a changing climate.

Theoretical and practical implications diverge somewhat in their emphasis. From a theoretical Earth system modelling perspective, the priority is resolving the mineral-association temperature sensitivity question and improving the representation of permafrost and multi-factor interactions, since these represent the largest sources of uncertainty in global carbon-climate feedback projections. From a practical land-management perspective, the priority is closer to reconciling carbon sequestration and nitrogen retention objectives, since practices that build soil organic matter for climate mitigation may inadvertently increase nitrogen cycling vulnerability, a tension that has received disproportionately little attention relative to its practical significance for climate-smart agriculture programmes.

Relating these findings to current developments in the field, it is notable that the trajectory of evidence over the past decade has consistently moved toward greater estimated soil carbon vulnerability to warming — from early, relatively optimistic assumptions of large stable soil carbon sinks, toward a more nuanced recognition that mineral protection, while real and important, is itself climate-sensitive, and that permafrost carbon once assumed to be essentially inert on human timescales is already contributing measurable net emissions in some regions. This trajectory underscores the importance of continued, sustained observational investment even as attention shifts toward newer methodological frontiers such as multi-omics and machine-learning-based upscaling.

7. Conclusion

This paper has pulled together scientific literature on the impact of climate change on soil carbon and nitrogen cycling in five key areas: how sensitive SOC decomposition is to temperature, the relationship between warming and precipitation and nitrogen cycling, the carbon feedback from permafrost, how microbes control the relationship between climate change and biogeochemistry, and options for managing carbon storage. An important finding across all of the areas discussed is that climate change does more than just accelerate the changes in biogeochemical processes; it shifts the type of soil carbon and nitrogen that is undergoing changes, in that what were once stable stores of carbon, such as deep mineral carbon and permafrost carbon, are becoming less stable.

The main significance of this work is about its use in climate predictions and land management. Solving the question of the sensitivity of temperature to mineral association and expanding the use of multi-factor experiments will reduce uncertainty in carbon-climate feedback calculations. In terms of land management and agricultural policy, findings show that sequestration of soil carbon must be performed in conjunction with considerations regarding nitrogen cycle and that a climate-smart agricultural practice must be focused on a joint optimization of carbon storage and nitrogen retention instead of concentrating on either process.

This review advises researchers to use multi-factor experimental designs that manipulate temperature, precipitation, and carbon dioxide levels together rather than treating them separately, and suggests a greater geographical and mineralogical range in studies on soil carbon temperature sensitivity, which tend to focus too much on temperate and boreal regions, as well as the need for a framework to study simultaneously carbon and nitrogen transformations. The review also suggests that those working on carbon-sequestering programmes, including 4 per 1000 Initiative and national climate mitigation commitments, should take into consideration the possibility of trade-offs and co-benefits of nitrogen cycling, ensure that carbon feedbacks from the permafrost are integrated into the accounting of national and international carbon budgets, and develop agricultural practices that apply nitrogen management at the same time with other climate-smart practices such as cover crops and reduced tillage.

Future research opportunities that could significantly contribute to this field include multi-decade manipulation studies that can track the gradual changes that occur in stable carbon pools, the use of enriched isotopes and multi-omics approaches to understand how changes in microbial communities affect biogeochemical processes at an ecosystem level, as well as the development of components of the global change modeling framework that take into account mineral-carbon relationships, permafrost carbon dynamics, and carbon-nitrogen linkages within a single modeling framework.

11. References

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