

Progress and prospects in understanding the effects of forest management practices on soil nitrogen cycling

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Abstract: Soil nitrogen (N) cycling plays a pivotal role in forest ecosystem productivity and nutrient regulation. This review synthesises recent advances in understanding how forest management practices influence soil nitrogen cycling and highlights future research priorities for elucidating underlying mechanisms and optimising forest ecosystem functioning (Figure 1). Management interventions such as thinning, species composition adjustment, and understory vegetation control have been shown to affect N inputs and transformation pathways by modifying litter quality, microbial community structure, and N-cycling enzyme activities. However, current findings remain inconsistent, and mechanistic insights are still limited. Future research should focus on disentangling the multi-scale, multifactorial interactions through which forest management regulates soil N cycling. Integrative approaches that link molecular biology with ecosystem-level processes are needed to clarify the interplay among microbial dynamics, enzyme activity, root exudates, and soil physicochemical properties across spatial and temporal scales. In addition, research should explore how forest management affects community structure, litter inputs, soil aggregation, and subsurface biochemical processes to reveal the synergistic regulation of nitrogen cycling by biological, physical, and chemical drivers. Establishing long-term monitoring networks across a range of forest types and climatic regimes, combined with tools such as metagenomics, high-throughput sequencing, and stable isotope tracing, will enable the precise characterisation of key nitrogen-cycling genes and fluxes. In the context of global environmental change, it is also crucial to assess how forest management modulates the coupling of nitrogen, carbon, and water cycles and the resultant ecological feedbacks.

Keywords: fertilisation; fire; rotation periods; soil microbial communities; structure and composition

Nitrogen is one of the most abundantly absorbed mineral nutrients by plants and plays a fundamental role in their growth and development (Kalbitz et al. 2003). It is also a key regulator of terrestrial ecosystem functioning. In many terrestrial ecosystems, nitrogen is often the primary limiting nutri-

ent for tree growth (Cabrera et al. 2025). In North America and Europe, nitrogen saturation has significantly altered forest ecosystem structure and function (Lovett and Rueth 1999). Soil nitrogen cycling is generally characterised by three core processes: nitrogen input, transformation, and output (Zang

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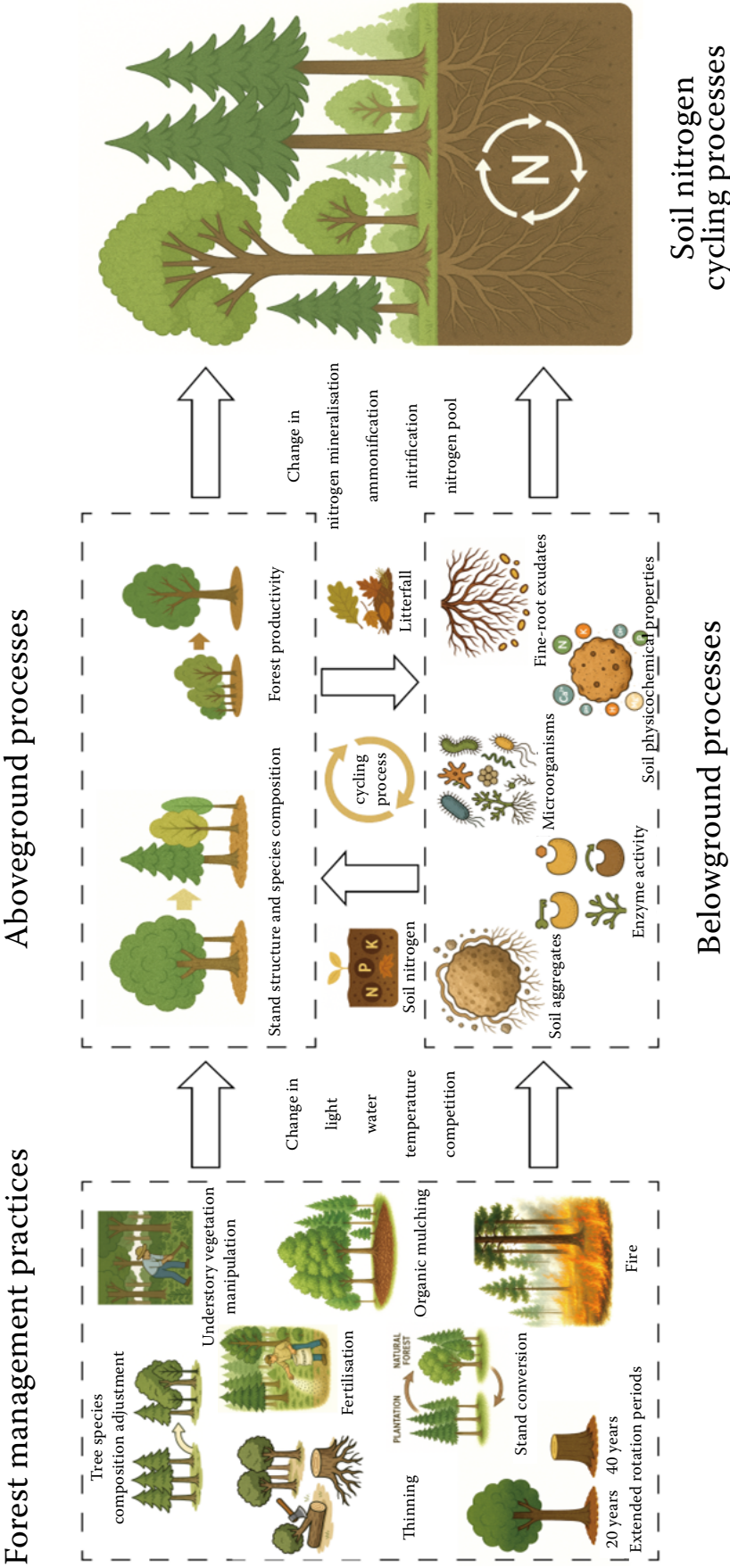


Figure 1. Mechanisms of different management practices and their impact on the soil nitrogen cycle

(A) Web of Science

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Node size – keyword frequency; link thickness – co-occurrence strength; different colours – distinct thematic clusters

bases (Figure 2). The primary objectives are to systematically assess the current research landscape, delineate prevailing knowledge gaps, and prioritise directions for future investigation. Such insights are intended to underpin the formulation of evidence-based forest management strategies and to advance mechanistic understanding of anthropogenic influences on belowground ecological processes.

Thinning substantially alters the forest micro-environment by increasing solar radiation at the forest floor, elevating soil temperature, and reducing both evapotranspiration and canopy interception. These alterations enhance soil moisture availability, which in turn influences microbial activity, soil physicochemical properties, and enzyme dynamics – factors that collectively regulate nitrogen (N) input, transformation, and loss processes. As highlighted by Kuypers et al. (2018), soil nitrogen transformations are predominantly microbially mediated, with the balance between microbial competition and cooperation shaping nitrogen pathways and end-products. Environmental variables exert indirect control over these microbial networks, which are increasingly recognised as key regulators of the stability and responsiveness of the soil nitrogen cycle.

In boreal *Larix gmelinii* plantations, 45% thinning intensity significantly enhanced soil multifunctionality and fungal diversity during the growing season, thereby promoting soil nitrogen cycling (Wang et al. 2023). Similarly, in *Cunninghamia lanceolata* plantations, thinning improved light and moisture conditions, elevated soil temperature, and stimulated microbial growth – leading to increased abundances of dominant fungal phyla such as *Ascomycota* and *Basidiomycota*, and elevated total soil N concentrations (Liao et al. 2024). In *Pseudotsuga menziesii* (Douglas-fir) forests of Canada, Levy-Booth and Winder (2010) observed that thinning elevated total soil carbon content, which in turn upregulated nitrogen-fixation gene abundance and stimulated microbial N fixation, thereby accelerating the overall nitrogen cycle. In subtropical forests, moderate (15%) and intensive (25%) thinning significantly increased nitrification rates by 87% and 61%, respectively, compared to unthinned controls (Yao et al. 2024). Although shifts in microbial community composition had minimal direct effects, elevated nitrogen availability enhanced ammonification and increased ammonium concentrations, thereby accelerating nitrification. Similarly, in *Pinus massoniana* plantations, moderate thinning enhanced total soil nitrogen content, with soil C:N:P stoichiometry identified as a critical modulator of nitrogen cycle responses (Jiang et al. 2022).

However, thinning may also reduce litter inputs, potentially suppressing N cycling. In *Pseudotsuga menziesii* (Douglas-fir) and *Cunninghamia lanceolata* (Chinese fir) plantations, high-intensity thinning (60%) drastically reduced above- and belowground biomass and litter inputs, which in turn decreased primary productivity and significantly depleted soil total nitrogen reserves (Gross et al. 2018; Zhou et al. 2023). In subtropical *P. massoniana* forests, thinning intensities of 44–57% were associated with reduced litter production and soil water-holding capacity, which led to increased nitrogen leaching and diminished soil N pools (Zhou et al. 2024a). In contrast, Ma et al. (2017) reported that light (25%) and moderate (45%) thinning increased autumn litter deposition and elevated concentrations of soil soluble organic nitrogen, likely due to differences in litter return dynamics under varying thinning intensities. Other studies have shown that thinning enhances forest floor light availability, soil temperature, and mois-

ture, thereby accelerating microbial activity and litter decomposition, which ultimately increases soil nitrogen availability (Chen et al. 2014). In *C. lanceolata* plantations, thinning intensities of 32% and 40% improved understory microclimatic conditions and litter quality, thereby facilitating decomposition and nutrient release, and ultimately enhancing soil nitrogen retention (Guo et al. 2020; Chen et al. 2023). Similarly, in Mediterranean black pine (*Pinus nigra*) stands, varying thinning intensities modified understory light conditions, thereby accelerating litter decomposition and subsequently altering soil nitrogen availability (Muscolo et al. 2007).

Thinning also modifies the structure and activity of soil microbial communities, thereby increasing the activity of key enzymes involved in N cycling. In mixed conifer–broadleaf forests, thinning at intensities of 20–30% increased the diversity of root exudates, litter composition, and understory plant species, which in turn stimulated the activities of soil sucrase, peroxidase, and acid phosphatase. These changes collectively contributed to increased soil total nitrogen and microbial biomass N concentrations (Xiao et al. 2016). In *Larix* plantations, thinning improved soil conditions and significantly upregulated N-acetyl- β -D-glucosaminidase (NAGase) activity, an enzyme involved in the degradation of chitin and other N-containing compounds, thereby facilitating the release of inorganic nitrogen (Mao et al. 2023). However, other findings (e.g. Zhou et al. 2019) indicate that although enzyme activities and organic matter decomposition were enhanced, accelerated nutrient mineralisation may have led to excessive organic matter depletion, ultimately reducing soil nutrient content. Such discrepancies are likely attributable to variations in vegetation type, soil properties, climate conditions, and background nutrient status. These findings underscore the importance of long-term, site-specific studies to clarify the mechanisms through which thinning influences enzyme activity and nitrogen cycling.

Moreover, the cascading effects of thinning on fine root biomass dynamics and their implications for soil nitrogen cycling remain poorly understood. Fine roots act as crucial conduits for nitrogen uptake and return at the plant–soil interface, and a shift in their biomass can influence soil N cycling through altered litter inputs, microbial interactions, and resource allocation patterns.

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IMPACTS OF TREE SPECIES COMPOSITION ADJUSTMENT ON SOIL NITROGEN CYCLING

Introducing nitrogen-fixing or functionally diverse tree species can improve soil physicochemical properties and increase organic carbon content, thereby enhancing microbial decomposition and mineralisation of organic nitrogen. The process promotes the release of inorganic nitrogen forms (e.g. NH_4^+ and NO_3^-) while simultaneously reducing gaseous nitrogen losses. Moreover, increased tree species diversity contributes to more chemically and structurally diverse litter inputs, which in turn enhances nitrogen inputs to the soil.

In *Cunninghamia lanceolata*–*Phoebe chekiangensis* mixed forests, compared with monocultures, tree species mixing enriched nitrogen-fixing bacterial taxa and increased the abundance of *nifH* gene-encoding diazotrophs, thereby enhancing the efficiency of soil nitrogen cycling (Ding et al. 2023). In *Eucalyptus*–*Mytilaria laosensis*–*Erythrophloeum fordii* and *Fagus longipetiolata*–*Liquidambar formosana*–*Carpinus turczaninowii* mixed stands, improved soil aggregate stability protected soil nitrogen from erosion and decomposition. Furthermore, greater tree species diversity promoted a more diverse and metabolically active microbial community. The chemically heterogeneous litter inputs supplied abundant labile carbon and nitrogen substrates, which in turn stimulated microbial activity and facilitated nitrogen cycling (Kooch et al. 2017; Yan et al. 2023). In *Pseudotsuga menziesii* plantations, the introduction of *Fagus sylvatica* reduced nitrate concentrations in the soil solution, lowering potential nitrate leaching risks and enhancing nitrogen turnover and utilisation efficiency (Mrak et al. 2024). Similarly, in *Larix principis-rupprechtii*–*Betula platyphylla*–*Quercus mongolica* mixed forests, litter exhibited a lower carbon-to-nitrogen ratio than monocultures, resulting in increased initial nitrogen availability and accelerated decomposition and nitrogen release. Additionally, elevated activities of urease and acid phosphatase in mixed forests facilitated organic nitrogen mineralisation, thereby increasing soil nitrogen content (Wang et al. 2021a).

In *Pinus massoniana* monoculture plantations, compared to mixed stands with *Eucalyptus*, *Mytilaria laosensis*, and *Castanea henryi* at a stand density of 2 500 trees per ha, nitrogen storage in the

upper, middle, and lower soil layers was higher by $1.23 \text{ g}\cdot\text{kg}^{-1}$, $1.02 \text{ g}\cdot\text{kg}^{-1}$, and $0.42 \text{ g}\cdot\text{kg}^{-1}$, respectively. This difference may be attributed to the accumulation of nitrogen resulting from the slow decomposition of *P. massoniana* litter, fungal-mediated nitrogen fixation, and the physical protection of nitrogen through carbon–nitrogen coupling, which collectively enhanced nitrogen retention in the upper and middle soil layers. In contrast, accelerated litter decomposition, intensified belowground competition, and reduced carbon stability in the mixed stands may have led to greater nitrogen losses and decreased soil nitrogen availability (Zhang et al. 2022).

The impacts of tree species composition adjustment on soil nitrogen cycling are modulated by multiple interacting factors, including species identity, environmental conditions, and forest management practices. The generalizability of current findings requires further validation through long-term, region-specific monitoring and experimentation.

ECOLOGICAL EFFECTS OF UNDERSTORY VEGETATION MANIPULATION ON SOIL NITROGEN DYNAMICS

Understory vegetation constitutes a vital component of forest ecosystems. Traditionally regarded as a competitor with overstory trees for soil moisture, nutrients, and growing space (Zhang et al. 2021), it was assumed to exert negligible influence on soil nitrogen levels, which was attributed mainly to inherent soil properties (Delgado-Baquerizo et al. 2015). Recent research, however, reveals that understory vegetation can significantly affect soil nitrogen inputs and transformations by altering microhabitats, contributing litter and root exudates, enhancing soil physicochemical characteristics, and stimulating microbial biomass and enzymatic activities.

In *Cunninghamia lanceolata* plantations, the retention of understory vegetation was found to enhance β -glucosidase and N-acetylglucosaminidase activities and ammonium availability by increasing carbon input and improving soil moisture conditions, thereby promoting organic matter decomposition and accelerating nitrogen cycling (Yang et al. 2016). In *Dacrycarpus imbricatus* forests incorporating the nitrogen-fixing shrub *Ceanothus arboreus*, the high-nitrogen and low-lignin litter provided by the N-fixing species mitigated microbial nitrogen limitation, lowered carbon

mineralisation demands, and elevated soil organic nitrogen accumulation (Winsome et al. 2017). Studies in cold-temperate *Larix* forests showed that understory vegetation dominated by *Sphagnum* mosses and *Rhododendron* significantly enhanced nitrogen mineralisation rates, highlighting the role of understory diversity in promoting nitrogen cycling (Xiao et al. 2025). In contrast, removal of understory vegetation often led to degraded surface microclimates – such as increased temperature and reduced humidity – declines in carbon input, inhibition of microbial activity, and disruption of soil nitrogen cycling. In *Pinus elliottii* plantations, understory removal led to more nitrogen being retained in undecomposed litter, thus reducing the availability of soil nitrogen (Qiao et al. 2014). In 48-year-old *Cryptomeria japonica* plantations, the removal of understory vegetation caused soil acidification, accelerated nutrient loss, and diminished nitrate nitrogen content in the soil (Baba et al. 2011). Similarly, in *Eucalyptus* and *Acacia yunnanensis* plantations, the removal of *Rhodomyrtus tomentosa* increased surface light intensity and depleted soil organic matter, thereby suppressing nitrogen mineralisation and nitrification in surface soils, with a more pronounced effect observed in *Eucalyptus* stands (Wang et al. 2014).

Current research on the influence of understory vegetation types on soil nitrogen cycling remains relatively limited in scope, with most studies emphasising soil enzyme activities and litter input dynamics. However, the mechanistic pathways through which these effects occur remain inadequately understood. Root exudates and soil microbial communities also play pivotal roles in mediating soil nutrient transformations, yet they have received comparatively less attention. To advance this field, future studies should prioritise the development of long-term experimental monitoring systems aimed at quantitatively evaluating the impacts of understory vegetation management on soil nitrogen cycling. Moreover, effects should be directed toward disentangling the interactive effects of multiple biotic and abiotic drivers on soil nitrogen dynamics.

IMPACTS OF STAND CONVERSION ON SOIL NITROGEN CYCLING

A meta-analysis indicated that converting natural forests into plantation systems, primarily through land clearing and reduced canopy shading, sig-

nificantly diminished litter inputs and microbial biomass. These alterations were accompanied by a 7.4% decline in the soil carbon-to-nitrogen ratio and a 39% reduction in N-acetylglucosaminidase activity. Consequently, soil nitrogen mineralisation rates increased, thereby intensifying nitrogen losses via leaching, surface runoff, erosion, and gaseous emissions (Wang et al. 2021b).

In Europe, the conversion of secondary natural forests to *Larix* plantations and *Fagus* forests to *Pinus thunbergii* plantations resulted in lower microbial biomass nitrogen in plantation soils. This decline was attributed to the dominance of recalcitrant litter components, which slowed decomposition rates and suppressed microbial activity (Kara et al. 2008; Yang et al. 2010). Similarly, replacement of evergreen broadleaved forests with *Sassafras tzumu*, *Cryptomeria fortunei*, or *Metasequoia glyptostroboides* resulted in substantially lower litter mass in the plantations, with natural forests exhibiting litter quantities 2.58-, 2.73-, and 1.42-fold higher, respectively. These changes were accompanied by reductions in soil microbial abundance and urease activity, which led to lower concentrations of total nitrogen, microbial biomass nitrogen, ammonium, and nitrate in plantation soils relative to natural forests (Gong et al. 2011). In *Cunninghamia lanceolata* plantations established on former natural broadleaved forest sites, the α -diversity of ammonia-oxidising archaea and bacteria declined, while the abundance of denitrification-related genes increased. These shifts collectively contributed to diminished ammonium availability in plantation soils (Guo et al. 2022). In contrast, conversion of natural coniferous forests to *Cedrus deodara* plantations triggered a fungal community shift from ectomycorrhizal to saprotrophic dominance, thereby promoting the mineralisation of organic nitrogen and resulting in the accumulation of inorganic nitrogen in soils (Sawada et al. 2023).

The impacts of stand type conversion on soil nitrogen cycling exhibit considerable variability across studies. While most current research has focused predominantly on litter quality, the complex interactions among litter traits, microbial community composition, and functional gene dynamics in driving the nitrogen transformation process remain insufficiently investigated. Furthermore, comparative studies at regional scales, particularly those encompassing diverse forest types and climatic conditions, are notably scarce.

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IMPACTS OF EXTENDED ROTATION PERIODS ON SOIL NITROGEN CYCLING

As a key silvicultural strategy, the rotation period modulates soil nitrogen dynamics by regulating vegetation growth cycles, litter inputs, and microbial activity. In *Cunninghamia lanceolata* plantations, short rotations (10–25 years) have been shown to intensify losses of inorganic nitrogen and microbial biomass nitrogen, particularly in soils derived from granite parent materials (Zhang et al. 2019). Although moderate-length rotation periods can partially offset nitrogen depletion through litterfall return, soil available nitrogen still tends to decline over successive planting cycles (Ma et al. 2007). In contrast, plantations with a 50-year rotation period exhibit greater annual nitrogen return and higher nitrogen cycling efficiency, thereby contributing to the stabilisation of soil available nitrogen over time (Xin et al. 2011). Consistent with these findings, research by Peng et al. (2002) and Jiang et al. (2002) in boreal forests of Canada and northern China indicated that, under equivalent harvesting intensities, soil available nitrogen was highest in long-rotation regimes and declined progressively with shorter rotations. Similarly, in Finnish silver birch and Scots pine stands, those with longer rotation periods exhibited greater nitrogen mineralisation potential and reduced nitrate leaching (Morozov et al. 2019).

However, the influence of extended rotation periods on soil nitrogen cycling varies markedly across forest types. In *Schima superba* plantations, nitrate concentrations and the activities of urease and sucrase peaked in 55-year-old mature stands but declined in 64-year-old overmature stands, likely due to accelerated litter decomposition and intensified root competition. Microbial functional gene analyses further indicated that reductions in soil calcium concentrations were significantly correlated with decreased abundances of genes involved in carbon, nitrogen, and phosphorus cycling, indicating that calcium may act as a critical regulator of soil nitrogen retention processes (Sun et al. 2025).

To date, most studies on the effects of rotation length on nitrogen dynamics have concentrated on *Cunninghamia lanceolata* plantations, while findings for other species remain comparatively scarce and often inconsistent. Moreover, the interactive effects between soil parent material and

rotation length remain poorly understood. Existing research has primarily focused on the influence of parent material shapes on soil physicochemical properties, whereas its role in structuring soil microbial community composition – and thereby regulating nitrogen cycling – has received limited empirical attention.

IMPACTS OF FERTILIZATION ON SOIL NITROGEN CYCLING

Fertilisation directly increases soil nitrogen inputs and stimulates forest net primary productivity. However, prolonged or excessive nitrogen application can induce soil acidification, which suppresses the activity of nitrifiers and denitrifiers, thereby disrupting key nitrogen transformation processes such as nitrification and denitrification. Additionally, excessive nitrogen inputs may facilitate nitrogen leaching losses, ultimately reducing soil nitrogen retention capacity.

Long-term studies by Aber et al. (1989) demonstrated that continuous nitrogen enrichment significantly accelerates nitrogen mineralisation in temperate forest soils. In subtropical ecosystems, nitrogen fertilisation has been reported to stimulate both nitrification and denitrification in *Phyllostachys edulis* (Moso bamboo) plantations, leading to elevated nitrate availability and microbial biomass nitrogen content (Liu et al. 2017). Similar enhancements in nitrogen mineralisation rates have been documented in *Cinnamomum camphora* plantations following nitrogen input (Wen et al. 2015). Comparable trends have been observed in coniferous forests across several European countries, including the United Kingdom and Sweden, where exogenous nitrogen inputs facilitated nitrogen transformation processes. However, studies conducted in the United States have revealed a nonlinear response: while moderate nitrogen additions promoted mineralisation, excessive inputs beyond a critical threshold inhibited the process, with rates falling below those observed in unfertilised controls (Magill et al. 1986). A similar pattern was identified in *Pinus elliottii* plantations in subtropical China, where nitrogen mineralisation rates increased with nitrogen addition up to 15 g·m⁻² but declined sharply when inputs reached 30 g·m⁻² (Zhao et al. 2012).

Nitrogen transformation in forest soils is governed by a complex interplay of biotic and abi-

otic factors. The influence of exogenous nitrogen inputs on soil nitrogen cycling is both temporally dynamic and mechanistically complex. As such, the underlying mechanisms by which nitrogen additions alter forest soil nitrogen dynamics warrant long-term, field-based experimental investigation (Zhao et al. 2012).

IMPACTS OF ORGANIC MULCHING ON SOIL NITROGEN CYCLING

Organic mulching refers to the application of mechanically processed or composted urban green waste to the soil surface surrounding urban trees and landscape vegetation (Zhou et al. 2022). When applied appropriately, organic mulching increases soil porosity and improves aeration, thereby facilitating nitrogen mineralisation, moderating nitrification and denitrification, and reducing nitrogen losses via leaching and volatilisation. However, excessive mulching can induce soil hypoxia, intensify denitrification, and ultimately lead to increased nitrogen loss.

In urban forest ecosystems, the application of different organic mulching materials has been shown to increase carbon inputs, alter microbial community composition, promote the mineralisation of organic nitrogen, and significantly elevate both total nitrogen and alkaline hydrolysable nitrogen levels in soils. Among the treatments tested, the combined application of wood chips and compost proved most effective (Zhou et al. 2024b). In bamboo plantations, organic mulching enhanced the inputs of cellulose-rich substrates, accelerated organic matter decomposition, and led to a notable increase in the concentration of easily oxidisable carbon with prolonged mulching duration. These changes stimulated microbial activity and thereby enhanced soil nitrogen content (Li et al. 2017). In *Ligustrum lucidum* stands, experiments with mulch layers of 5 cm, 10 cm, and 20 cm demonstrated that moderate mulch thickness may promote microbial biomass nitrogen accumulation in rhizosphere soils by stimulating microbial processes and facilitating rapid nitrogen turnover, whereas excessive mulch thickness may impede water infiltration and limit nitrogen availability (Sun et al. 2021).

As an effective practice for improving soil structure and facilitating nutrient cycling, organic mulching has been widely applied in forest man-

agement. However, its regulatory effects on soil nitrogen cycling remain insufficiently understood. Existing studies are typically short-term and focus primarily on the immediate to mid-term effects of mulching on nitrogen distribution, providing limited insight into its long-term influence on nitrogen dynamics. Furthermore, soil nitrogen cycling under mulching treatments is highly sensitive to environmental factors such as soil moisture and temperature, thereby limiting the generalisability of findings across different ecological regions.

IMPACTS OF FIRE ON SOIL NITROGEN CYCLING PROCESSES

Fire is a critical driver of nitrogen cycling in forest soils. Disturbance by fire reduces the cover of nitrogen-fixing plants and suppresses soil microbial activity, thereby decreasing nitrogen inputs. Furthermore, post-fire increases in soil temperature and pH, shifts in microbial community composition, and altered soil moisture conditions collectively stimulate nitrification and denitrification, exerting strong influences on nitrogen transformation processes. Combustion also volatilises soil nitrogen, releasing it into the atmosphere as gaseous emissions and thereby intensifying nitrogen losses.

A meta-analysis of temperate forests demonstrated that fire generally reduces nitrogen concentrations in the humus layer, while exerting relatively limited effects on the organic layer (Nave et al. 2011). This pattern arises because combustion of the humus layer results in volatilisation of organic nitrogen, whereas deposition of ash enriched with alkaline cations tends to increase surface soil pH and elevate ammonium nitrogen concentrations after fire (Certini 2005). Additionally, post-fire rainfall promotes nitrate migration, thereby enhancing nitrogen leaching and inputs into aquatic systems (Paul et al. 2022).

Fire also exerts profound effects on soil microbial communities. Elevated temperatures and substrate depletion initially suppress microbial biomass, but subsequent recovery is characterised by shifts in community composition, with increased abundances of nitrifiers and ammonia-oxidising microorganisms. These changes enhance nitrogen mineralisation and nitrification, leading to short-term increases in NO and N₂O emissions (Covington, Sackett 1992; Stephens, Homyak 2023; Guo

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et al. 2024). Fire-derived pyrogenic organic matter (PyOM) creates a char-rich soil environment that adsorbs inorganic nitrogen and modifies soil moisture and redox conditions, thereby altering nitrogen transformation and retention (DeLuca et al. 2006; Ball et al. 2010).

Vegetation responses to fire further modulate nitrogen inputs and turnover. Nitrogen-fixing species are often severely damaged, reducing biological nitrogen fixation and aggravating nitrogen limitation (Wong et al. 2020). However, in some temperate forests, the recovery of nitrogen-fixing shrubs during post-fire succession can partially offset nitrogen losses (Yelenik et al. 2013). For example, research in North American ponderosa pine forests indicated that prescribed low-intensity burning removed surface humus while promoting rapid inorganic nitrogen release in mineral soils, without inducing long-term nitrogen limitation (Covington, Sackett 1992). In Yellowstone National Park, severe wildfires resulted in soils dominated by ammonium nitrogen during the first post-fire year, whereas nitrate nitrogen peaked two years later, reflecting marked temporal differentiation (Turner et al. 2007).

Current research on fire effects in forest soil nitrogen cycling has mainly addressed short-term post-fire responses, whereas knowledge of long-term nitrogen storage recovery and its linkage with forest succession is still limited. Studies are concentrated in Europe and North America, with insufficient attention to arid, tropical, and high-latitude forests. At the microbial level, investigations into functional gene dynamics, their coupling with nitrogen transformations, and the role of fire-derived organic matter remain scarce. Moreover, most research has focused on wildfires, while the ecological consequences of prescribed low-intensity burning are inadequately explored, constraining its application in sustainable forest management. Future efforts should emphasise long-term monitoring, broaden spatial coverage, employ molecular and isotopic techniques, refine measurements of gaseous nitrogen fluxes, and strengthen integration with fire management practices.

CONCLUSION

Although numerous studies have explored the effects of forest management practices on soil nitrogen (N) cycling, most have primarily fo-

cused on thinning intensity and stand structure adjustment. However, the cascading impacts of management on aboveground vegetation dynamics and belowground nitrogen transformation remain underexplored. In addition, existing studies are often constrained to limited spatial and temporal scales and lack long-term observational networks. Future research should therefore prioritise the following directions:

- (i) Elucidate how different management practices regulate key factors and their interactions that drive soil nitrogen cycling. A multi-scale research framework, spanning from the molecular level (e.g. functional gene expression and microbial metabolic networks) to ecosystem, regional, and global scales, should be integrated through site-based monitoring networks. Emphasis should be placed on disentangling the spatiotemporal dynamics and feedbacks among biotic components (e.g. microbial community composition and function, root exudates, and enzyme kinetics) and abiotic factors (e.g. soil physicochemical properties and microclimatic variables).
- (ii) Investigate the downstream effects of management interventions on community structure, ecosystem productivity, litter input and quality, and belowground nitrogen processes. Particular attention should be given to understanding how carbon and nutrient fluxes, fine root and litter decomposition, enzyme activities, soil aggregation, and soil physical properties jointly regulate nitrogen cycling through interconnected biological, chemical, and physical pathways.
- (iii) Develop long-term, in-situ monitoring networks that span major forest types and climatic zones to systematically track changes in soil nitrogen pools, transformation rates, key microbial functional groups, and enzyme activities. These data will support the identification of optimal management regimes and spatiotemporal strategies for enhancing soil nitrogen cycling and ecosystem function.
- (iv) Apply high-throughput sequencing approaches, including metagenomics and metatranscriptomics, to precisely characterise shifts in the abundance, composition, and transcriptional activity of nitrogen-cycling functional genes in response to management. Integrating these molecular tools with

enzyme assays and substrate utilisation profiling will enable the construction of holistic frameworks linking microbial community structure, functional gene expression, and nitrogen transformation rates. Stable isotope techniques should be employed to trace nitrogen fluxes and transformation pathways under different management regimes. In parallel, deployment of high-resolution in situ sensors and implementation of microcosm experiments can reveal how altered rhizosphere conditions mediate nitrogen speciation and root–microbe symbioses.

- (v) In the context of global environmental change, further research is needed to examine how forest management modulates the coupled nitrogen, carbon, and water cycles. Special emphasis should be placed on assessing the sensitivity, adaptability, and feedback mechanisms of soil nitrogen cycling to global drivers. Evaluating the capacity of various management strategies to buffer against global change impacts or to enhance ecosystem resilience will be critical for sustainable forest management.

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