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Soil nitrogen dynamics in natural forest ecosystem: a review

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Nitrogen (N) is an important component of the forest soils and plays a pivotal role in the ecosystem's health, also in broadleaf and Moso bamboo (*Phyllostachys edulis*) forests. Nitrogen plays numerous functions in the production and transformation of soil organic matter (SOM) and alterations in the soil's physicochemical and biological properties. Despite the extensive research on soil properties and microorganism diversity in broadleaf and Moso bamboo forests, we still know very little about N dynamics and its significance in broadleaf and Moso bamboo forests, or how various physical and environmental variables influence soil physicochemical, N dynamics, and biological attributes. This article provides a thorough overview of the role of N dynamics in broadleaf and Moso bamboo forests and changes in soil physicochemical properties processes by summarizing recent advances in our knowledge of forest soil microbial diversity, and carbon (C) and N sink in broadleaf and Moso bamboo forests. As broadleaf and Moso bamboo forests are very sensitive to little change, even a small change in these ecosystems can alter the overall N dynamics. Here, we dissect the soil ecology of broadleaf and Moso bamboo forests to provide insights into the possibilities and consequences of future studies of N dynamics in these ecosystems.

KEYWORDS

forest ecosystem, bamboo invasion, nitrogen cycling, broadleaf forests, soil properties

1. Introduction

Due to the function in the production and transformation of soil organic matter and transformation of forest soil physicochemical and biological attributes, Nitrogen (N) plays a pivotal role and important component of the forest soil ecosystem's health, especially in broadleaf and Moso bamboo (*Phyllostachys edulis*). Soils contain less than 1% of the world's total N, while other is stored in the atmosphere and sedimentary rocks that are thus unavailable to plants (Follett and Hatfield, 2001), which ultimately affect the forest tree development. Litterfall, biological N fixation (BNF), recycling of tree leftovers, and microbial transformations and bodies are all many of the N sources in forests (Sponseller et al., 2016; Tang et al., 2018), while the N cycle is also governed by these factors in addition to soil organic matter (SOM) breakdown via climatic conditions and/or forest fires, etc. The mineralization-immobilization turnover is one process in the N cycle that is directly influenced by the N, which in turn modifies a variety of other ecosystem processes and functions, such as the soil nutrient cycles, i.e., N cycle and forests ecosystem functionality of the forests (Cheng et al., 2019; Kurniawan et al., 2019). The amount of N released during SOM decomposition directly

influences the amount of N consumed by soil microorganisms, and then the mineralization rate. In the N cycle of the forest soils, nitrification/denitrification and ammonification are important key steps. Ammonia (NH_3) is converted to nitrite (NO_2^-) by ammonia-oxidizing archaea and ammonia-oxidizing bacteria, while nitrite (NO_2^-) is converted to nitrate (NO_3^-) by nitrite-oxidizing bacteria (Isobe et al., 2018a).

Many crucial ecological and physiological processes in forest ecosystems rely on the activities of soil microbial communities, including N and SOM turnover, the control of mineral nutrient availability, the fixation of atmospheric N, and the development of mycorrhiza (Zhou et al., 2020; Matos et al., 2021; Wang et al., 2022a). Soil microbial populations produce hydrolases to break down plant litter and other organic materials (Tan et al., 2020), recycling nutrients and promoting plant growth as part of the nutrient cycle process in forest environments (Prasad et al., 2021). Soil microbial communities, through controlling the rate of microbial decomposition of SOM, may influence soil attributes including nutrient concentration (Kooch and Noghre, 2020), and hydrolase activity (Wu et al., 2021). Multi-dimensional soil characteristics such as nutrient content, moisture, and pH also affect soil microbial populations. In a similar vein, immature Moso bamboo and broadleaf forest species, a huge woody clonal plant, relies on regular nutrition delivery through clonal integration to develop rapidly. Moreover, the release of BNI substances in the rhizosphere by some forest tree species could also affect N dynamics (Wang et al., 2021). So, an explanatory document about N fixation and inhibition in rhizospheric and bulk soils of Moso bamboo and broadleaf forests is missing in spite of a few short reports in the last several years on how clonal integration affects nutrient transport and allocation in Moso bamboo by Shi et al. (2022). But the N dynamics under different factors and environmental stress conditions remain unclear. In this review, we have summarized the N dynamics in rhizospheres of moso bamboo and broadleaf forests in the presence and absence of BNI substances and environmental factors with the significance of N dynamics in Moso bamboo and broadleaf forests.

2. Nitrogen: importance in soil, and plant lifecycle

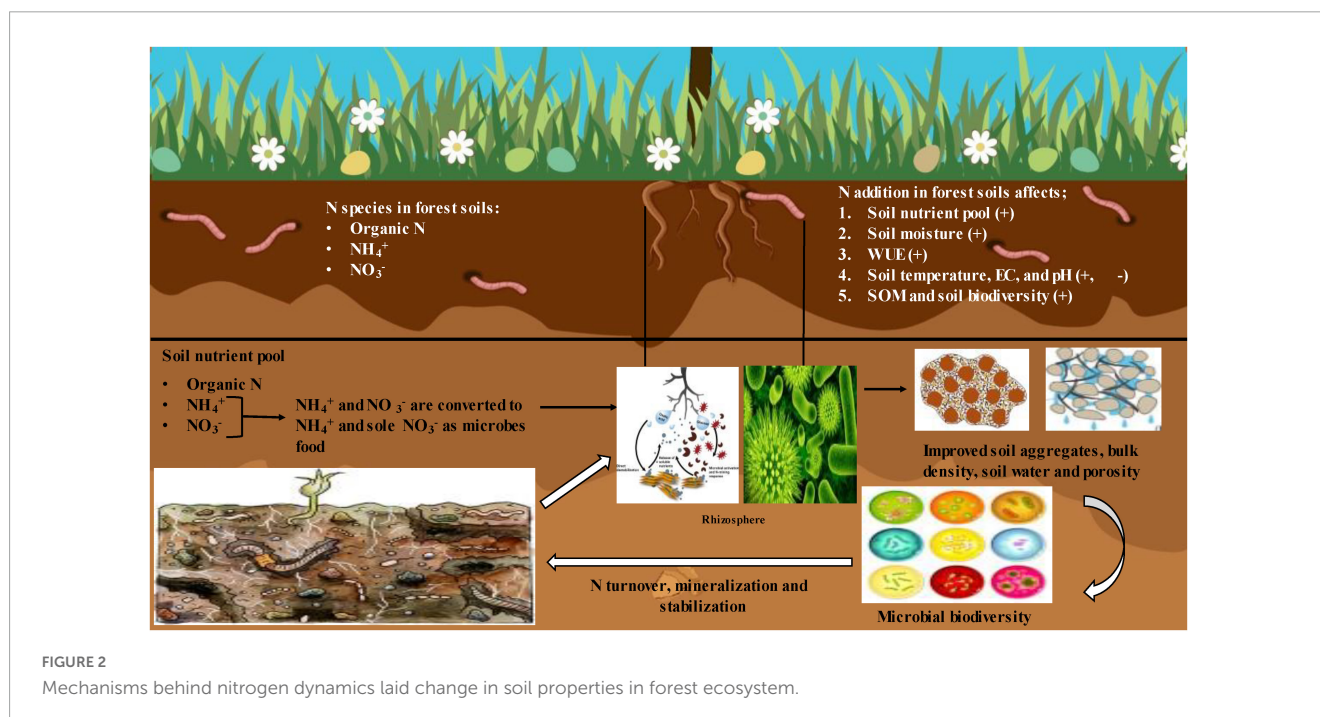
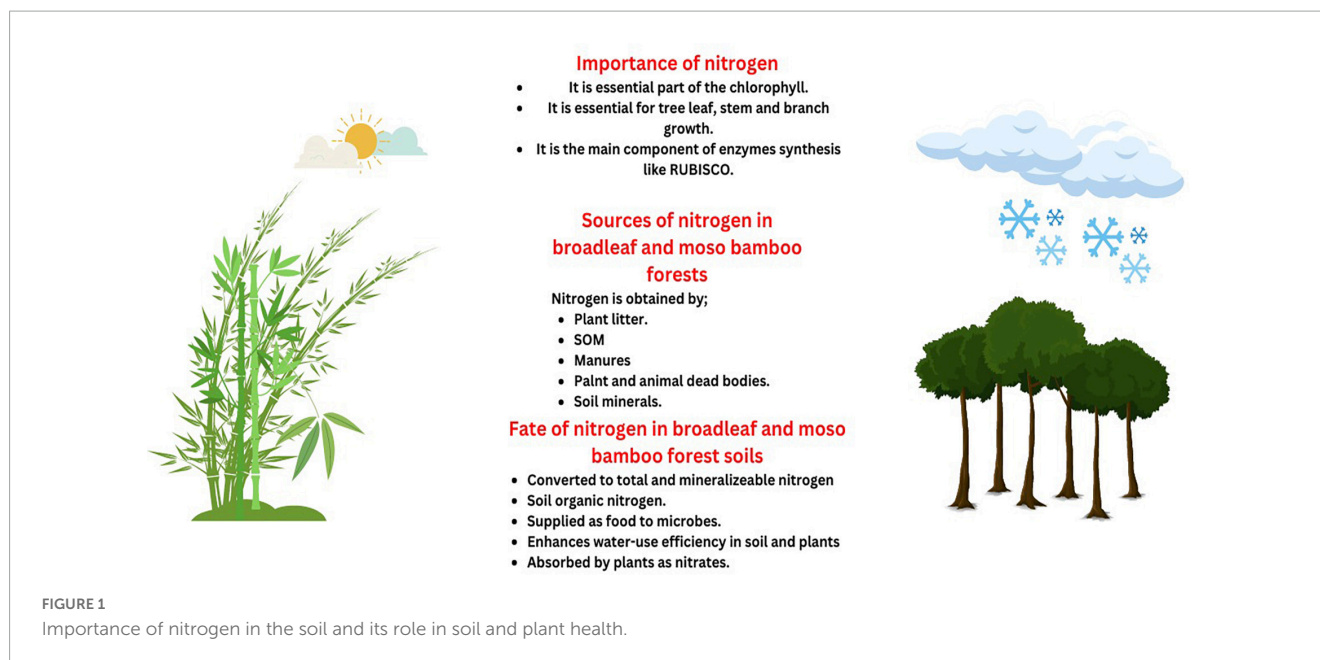
Nitrogen is an essential element for plant growth and is a crucial component of forest ecosystems. It is one of the primary nutrients that plants need to synthesize proteins, enzymes, and other essential molecules. It is also a critical limiting factor in many forest ecosystems, meaning that its availability can significantly affect the productivity and health of the ecosystem (Lobell et al., 2004; Kumar et al., 2020; Yan et al., 2020). Nitrogen also plays a vital role in the cycling of nutrients within forest ecosystems. It is taken up by plants from the soil and incorporated into their tissues (Tian et al., 2019). When plants die and decompose, N is released back into the soil, where it can be taken up by other plants or processed by microorganisms. It is also essential for the growth of soil microorganisms, which are critical for nutrient cycling in forest ecosystems (Perakis and Pett-Ridge, 2019). The N in forest trees is found in biological substances (up to 60%) and only a small percentage is found in mineral forms like ammonium

(NH_4^+) and nitrate (NO_3^-) (Evans and Poorter, 2001; Geisseler et al., 2010). It benefits the trees in many ways, i.e., it boosts the soil water-use efficiency (WUE), and soil serves as an anchor for the expansion and development of tree roots (Shi et al., 2020; Li Y. et al., 2021). When N is up-taken by roots, it regulates and enhances tree growth (Guan et al., 2019; Muhammad et al., 2022). Moreover, N presence in the forest soils accelerates the SOM storage and concentration due to thorough microbial communities manipulation. The N in plant and animal dead bodies stimulates soil microbial activity (Allison et al., 2008). Its concentration also affects residue decomposition and affects nutrient concentration in soils (Drost et al., 2020), and increases phosphorus (P) absorption by the plant by providing acidic compounds in soil and creating an acidic environment which is favorable for nutrient bioavailability to plants (Vitousek and Denslow, 1986). The N in broadleaf and bamboo forests enters via atmospheric deposition, soil minerals, rock weathering, and BNF (Lilleskov et al., 2019). In both types of forests, the cycling of N is largely driven by microorganisms, which play a key role in the decomposition of SOM and the conversion of N between different forms (Mushinski et al., 2021). The N can be immobilized by microorganisms and incorporated into their biomass or can be released back into the soil as inorganic forms (Dong et al., 2019a). However, there are some notable differences between nitrogen dynamics in broadleaf forests and bamboo forests. Moso bamboo is a fast-growing, woody grass species that has unique physiological characteristics, including a high demand for N and a unique root system that can rapidly take up and transport nutrients (Zheng et al., 2021). As a result, bamboo forests typically have higher rates of N uptake and cycling compared to broadleaf forest species.

Additionally, N dynamics in bamboo forests can be influenced by the cultivation practices used for bamboo production. For example, N fertilizers may be applied to promote bamboo growth, which can alter N cycling and have negative impacts on soil and water quality if not managed properly. The detailed importance and fate of N in the broadleaf and bamboo forest tree life cycle and soil biogeochemical cycles are summarized in Figure 1.

3. Global scenario of N dynamics in forest ecosystems

There are over 60,000 tree species in different types of forests worldwide (United Nation's Environment Program, 2022). So, one of the most significant areas of the study is N dynamics and its enrichment in forest ecosystems owing to its great influence on the forest ecosystem (Reis et al., 2017). Different biotic and abiotic components of the forest ecosystems influence N dynamics, i.e., mycorrhizae. Mycorrhizae works in soils for the decomposition of SOM found in tree litter and dead bodies in the form of different organic complexes, e.g., lignin, and cellulose (Martin et al., 2022; Ward et al., 2022). Along with fungi, bacteria and forest restoration also play crucial roles alone and in combination with fungi in the N cycle as indicated by Wang et al. (2022e). Forests dominated by *Oligotrophic Acidobacteria* and *Actinobacteria* shifted to be predominated by *Copiotrophic Proteobacteria* and *Firmicutes* after forest restoration (Selmants et al., 2016). Higher C and N stoichiometry in the litter-soil-microbe continuum is mostly



because of soil bacterial diversity, whereas increased plant variety is due to tree litter decomposition. But the composition of soil microbes was inversely linked to litter biomass, in addition to N concentrations. The N dynamics and soil microbial community structure along with their functions are also influenced by the tree diversity. Lower plants play a significant role in soil N availability, N mineralization rate, soil bacterial community build-up, and biomass in the top 10 cm of soil compared to deeper horizons. As reported by Xiao et al. (2022), who noted a stronger relationship between soil microbial biomass and N mineralization than there was between soil N content and N mineralization. This indicates that soil N mineralization is affected by forest type and soil microbial biomass. Moreover, soil bacterial composition was also

found to have a significant effect on soil microbial biomass, i.e., *Actinobacteria*, *Patescibacteria*, and *Chloroflexi* (Xiao et al., 2022).

Long-term N addition (10 years) has been also reported to be having negative effects on N concentrations in bamboo and other forest ecosystems as indicated by Wang et al. (2022b). In another study, Neves et al. (2022) reported that season and the predominance of various functional groups influence the dynamics of litter and the intake of nutrients in a secondary seasonally dry tropical forest. There may be phenological synchronization across various functional groups since litterfall output was much greater during the two driest months of study. Moreover, trees of the legume family dominated the greatest diameter class, reaching

double the basal area of non-legumes. In comparison to non-legume trees, legume trees doubled the quantity of N storage which was dropped throughout the winter. Moreover, altered N addition or mineralization can cause a significant change in soil microbial communities. Soil microbial communities, dissolved organic N, and litterfall all were affected by increased soil water content (Yu et al., 2022). Forest fires also affect the N dynamics in different forest ecosystems during the recovery period and can cause a ninefold increase in soil NH_4^+ -N and a threefold increase in soil NO_3^- -N concentrations in top soils after 2 years (Xu et al., 2022). **Table 1** summarizes the N dynamics in different broadleaf forest and bamboo forest ecosystems around the world.

4. Nitrogen dynamics in forest soils

In forests, the soil is continuously enriched with plant litter, dead animal and prey bodies, and plant dead wood (Tang et al., 2018). Therefore, the N cycle is different from agricultural soils along with the factors affecting it as it is majorly regulated by the tree community (Nie et al., 2018; Qin et al., 2019). Tree species determine the nature of N cycling and dynamics (Mushinski et al., 2021). Moreover, soil microbial community and N dynamics change due to several factors like forest fires and N addition from synthetic sources, i.e., microbial community structure, precipitation, soil properties, and litterfall (Yokobe et al., 2018; Tahmasbian et al., 2019; Purwanto and Alam, 2020; Xiao et al., 2020) (**Figure 2**). Below are the factors which majorly affect the N fixation and cycling in forest ecosystems.

4.1. Forest type and N dynamics

As soil under different forest ecosystems inhabitants large amounts of flora and fauna, they also have associated nutrients in the form of SOM and minerals (Dhaliwal et al., 2019; Sun Y. et al., 2021), only a minor alteration in the forest ecosystem can result in a greater response in forest tree species as different factors favor different tree species (Xing et al., 2022). In a study, Isobe et al. (2018b) reported altered N dynamics with the change in tree species as N transformations were driven by the type of tree species and their litterfall, as well as its decomposers' population diversity. Moreover, some tree species have BNI or BNF characteristics and they greatly influence N dynamics (Ramm et al., 2022). In the same way, different forest ecosystems carry the same responses, i.e., if tree species are replaced with other species, N dynamics changes accordingly. Su et al. (2021) reported the same phenomena in the subtropical forests of China where a change in forest tree ecology resulted in altered nutrient cycles. **Table 2** summarizes the N dynamics and their drivers in the numerous forest ecosystem. It can be seen that tree species can influence the N dynamics in a forest ecosystem.

4.2. Factors affecting N dynamics in forest soils

Soil microorganisms, forest fires, litterfall, nutrient addition, temperature, and soil characteristics are only a few of the

primary elements influencing N dynamics in a forest ecosystem. The availability of N is a significant factor limiting the forest's primary productivity.

4.2.1. Tree species

Forests are rich in tree diversity (Schiefer et al., 2020; Babur et al., 2021), and these different kinds of trees have different ecosystem services, e.g., some act as N fixers (Batterman et al., 2018), and some act as a source of N when become dead or both (Thorn et al., 2020), or litter is fallen from them (Lyu et al., 2018; Smith and Wan, 2019). The N-fixing black locust (*Robinia pseudoacacia*) trees work as N fixation. Black pine (*Pinus thunbergii*) trees and a mixed stand with black locust trees had higher N-fixing ability when assessed in a study from 2000 to 2019 time period. Cárdenas et al. (2022) reported that using an N-fixing legume and one non-legume tree species in a tropical dry forest results in similar performances across N-fixing and non-fixing legumes in the study area. Similarly oak and non-oak tree species also have different plant litter decomposition rates (Babl-Plauche et al., 2022).

4.2.2. Soil biota

Soil organic matter and humus are produced by the action of microbes. Its mineralization is also governed by soil fauna and flora (Komarov et al., 2017). Wang et al. (2022c) reported more earthworm growth in older forest soil compared to younger forest soil in response to more SOM concentration in older forest soil. The abundance of fungi also has similar effects as indicated by Osono (2015) that fungi pose a prominent role in N dynamics across a variety of forest ecosystems. The bacteria and earthworms in the soil also have reactions to the various functional kinds of plants. Francini et al. (2018) reported that soil microbial and nematode populations vary in natural and urban forests depending upon management, with mostly higher biota in a natural ecosystem, where N is governed by enzymes like arylsulfatase and phosphodiesterase. Earthworms also regulate N dynamics through their diversity and number. Groffman et al. (2015) concluded that N pools in earthworm-colonized plots were more stabilized than in forests dominated by *L. rubellus*, indicating earthworms help move N from litter into stable SOM and boost the soil microbial biomass. Fugère et al. (2017) reported that N transport in soil was higher with multi-species earthworm communities.

4.2.3. Forest fires

About 360 to 380 million hectares of forest area are lost each year due to forest fires, affecting forest soil biogeochemical cycles (Butler et al., 2020; Rabin et al., 2022), by altering soil pH, electrical conductivity (EC), microbial populations, and associated biochemical processes. Forest fires cause the melting of permafrost and remove the insulating layer of SOM, and raise soil temperatures (Aaltonen et al., 2019). The decomposition of plant organic matter is an essential part of the biogeochemical cycle on land and has a significant impact on both the fire fuel load and the C balance of forests. Butler et al. (2020) tested whether three alternative long-term fire regimes (no burning, 4-yearly burning, and 2-yearly burning) were linked to altered N dynamics during litter decomposition by conducting a 277-day experiment in an Australian eucalypt forest. The greatest rates of decomposition and C loss were seen in the no-burning treatment. Hu et al. (2020)

concluded after a study in mixed coniferous (*Pinus massoniana* Lamb.) and broadleaf (*Quercus acutissima* Carruth.) forests in China that after 3 months of forest fire, the soil pH, NO_3^- -N concentration, and microbial biomass carbon (MBC) were increased. Four weeks following a fire, the total aboveground biomass in the burnt plots was 39% less than in the unburned plots. In another study, James et al. (2018) reported that over 45 years after a forest fire, changes were still visible in the organic horizon and mineral soil characteristics. Albert-Belda et al. (2022) also reported similar results that burned soils had less microbial biomass compared to unburned forest sites, and burned soils were dominated by gram-positive bacteria.

4.2.4. N addition

Nitrogen addition plays an important role in soil biogeochemical cycles in forest ecosystems depending upon the forest tree species, amount of N added, and environmental conditions. Chen et al. (2020) reported that N addition in two different forests with different tree species did not affect SOM and soil organic carbon (SOC). Chen et al. (2016) and Lu et al. (2011) reported similar results that inorganic N, nitrous oxide (N_2O) emissions, and NO_3^- leaching all increased noticeably as a consequence of excessive N addition during 6 years. In another study, the decomposition constant increased by 46% as a result of the N addition. N addition reduced the strong association between litter and decomposers that accelerated the breakdown of home litter and caused stimulated N release from decomposing litter, with plant species effects moderating this process (Cui et al., 2017).

4.2.5. Litterfall

Litterfall is one of the most important factors in forest ecosystems which supply C and N after their decomposition through soil microbes. Bohara et al. (2020) reported that the

release of P, potassium (K), C, and N rates followed the order of $\text{P} > \text{K} > \text{C} > \text{N}$ from forest trees, suggesting that litter is a major sink of N. In another study, Kamruzzaman et al. (2019) reported C and N content of litterfall decomposition up to $1005.9 \text{ g m}^{-2} \text{ year}^{-1}$.

4.2.6. Soil properties

Soil properties were altered with altered N in terms of pH, EC, N, SOM, and P (Lucas-Borja et al., 2022). Siwach et al. (2021) reported that mosses alter soil properties by altering the soil's capacity to hold nutrients. Xiong et al. (2022) reported that N availability and fluctuations in the microbial community cause significant seasonal changes in the composition of the soil microbiome over an elevation gradient. Molla et al. (2022) concluded that natural forests had the highest concentrations of clay, pH, SOM, N, P, exchangeable bases (Ca^+ , Mg^+ , K^+ , Na^+), and cation exchange capacity (CEC). The soil pH, clay, bulk density (BD), and exchangeable bases all improved/increased with depth across all land use change categories in forests.

4.2.7. Root structure and activity

Mutualistic relationships between tree roots and the soil are how trees get access to the water, nutrients, and minerals in the soil (Authier et al., 2022). Forest ecosystems rely heavily on fine roots for N cycling. Dead roots have more N compared to other tree parts (Hu et al., 2022). Fine roots play a crucial role in the N dynamics of forests, including Moso bamboo forests by uptake absorbing more N from the soil, which is then used for plant growth and metabolism (Drake et al., 2011; Bai et al., 2016). Some tree species have symbiotic relationships with N-fixing bacteria in their fine roots, which converts atmospheric N into a form that plants can use (Wang H. et al., 2019; Staccone et al., 2020). Moreover, decaying fine roots contribute to the forest floor litter

TABLE 1 Global extent of bamboo invasion into the broadleaf forest ecosystem.

Area	Forest type	Climate	Driving force/Major finding(s)	References
Zhejiang, China	Moso bamboo forest	Temp. 15.9°C Prec. 1420 mm	Soil microbial populations changed as a result of bamboo invasion.	Xu et al., 2015
Fujian Province, China	Subtropical forest	Temp. 8.50–18.0°C Prec. 1486–2100 mm	An increase in the soil potential for fungal breakdown leads to greater nitrogen mineralization. The rates of nitrification and net ammonification in soil improved. Overall, the ammonification rate was 11 times greater than the nitrification rate.	Chen et al., 2021
Kyoto, Japan	Broad-leaved secondary forest	Temp. 15.3°C Prec. 1459 mm	<i>P. pubescens</i> dominated the stand and plant biomass was distributed and affected C and N stocks by its pre-dominance.	Fukushima et al., 2015
Fukuoka, Japan	Broadleaved forest	Temp. 16°C Prec. 1790 mm	Soil-water content spatial variance was higher in the bamboo stand than in the broadleaf stand.	Shinohara and Otsuki, 2015
Tamil Nadu, India	Reed Bamboo	Temp. 13.5–23°C Prec. 2000–3000 mm	Controlling Encroaching species is crucial for preserving forest ecosystems' diversity, productivity, and stability.	Dutta and Reddy, 2016
Bengal in India and western Bhutan	Maling bamboo	–	Species richness and density decreased significantly ($p < 0.0001$) as the proportion of bamboo in an area rose.	Gaira et al., 2022
Hiroshima, Japan	Temperate forests	Temp. 13.5°C Prec. 1446 mm	The introduction of Moso bamboo altered the makeup of the microbial communities present in the organic and mineral soil fractions and caused a decrease in SOM breakdown in the organic layer and an increase in deep soil C decomposition in the mineral layer, both of which may have repercussions on plant development.	Wang et al., 2016c
Shanlinshi, Taiwan	Subtropical forest	Temp. 17°C Prec. 2600 mm	Chemical composition and humification of soil organic matter are altered when Moso bamboo invades a Japanese cedar plantation.	Wang et al., 2016b

TABLE 2 Global scenario of forest types and nitrogen dynamics.

Forest type	Area	Climate	Driver of N dynamics/Main findings	References
Coniferous and broadleaf forest	Fujian, China	Subtropical region	Soil microbial biodiversity drive N dynamics. About 82% of soil organic nitrogen is found in soil TN.	Xing et al., 2010
Coniferous and broadleaf forest	Mohe, China	Mean annual temp. = -5.5°C mean annual Precp. = 425 mm	Soil protease activity, NH_4^+ -N, and total phosphorus are correlated with soil fungi, while K is correlated with soil fungi and bacteria.	Vuong et al., 2020
Coniferous forest	Borneo, Malaysia	Mean annual temp. = 18°C mean annual Precp. = 2714 mm	Plant-soil feedbacks are the main reason for structuring the forest tree diversity/community and important factors in plant functional feedback include tannins, soil saprophytic microbes, root-fungal interactions, and tree functional characteristics.	Ushio et al., 2017
Subtropical forest (coniferous)	Guangdong, China	Mean annual temp. = 21°C mean annual Precp. = 1927 mm	Long-term C storage is affected by changes in forest tree species mix and soil texture. Broadleaf forest has more macro aggregates. Soil C sequestration capacity is affected by changing tree species due to effects on macro-aggregate formation, soil chemical characteristics, and microbial biomass.	Su et al., 2021
Coniferous forest (urban forest)	Nanchang, China	Mean annual temp. = 17.5°C mean annual Precp. = 1600–1800 mm	N:P was greater in the fall and winter than in the spring and summer. Atmospheric N deposition and soil P enrichment led to an altered N and P status in the urban forest compared to natural forests.	Fan et al., 2014
Conifers	São Paulo, Brazil	Mean annual temp. = 21°C mean annual Precp. = 1350 mm	No differences in soil C dynamics between vegetation.	Cook et al., 2014
Boreal forest	Ontario, Canada	Mean annual temp. = 1.90°C mean annual Precp. = 824 mm	The impacts of shrub cover on plant communities in the boreal zone are complex, ranging from facilitative to inhibitory. Vegetation quantity and variety in the forest are determined by colonization, light availability and heterogeneity, and substrate heterogeneity.	Kumar et al., 2018
Nothofagus forest	Southern Patagonia, Argentina	Annual temp. Range = -0.6 to 10.9°C mean annual Precp. = 545 mm	Cationic exchange capacity (CEC) and pH are affected by Nothofagus forests.	Toro-Manríquez et al., 2019
Native broadleaf forest	Pingxiang, China	Annual temp. Range = 21°C Mean annual Precp. = 1400 mm	Non- N_2 fixing native broadleaf trees affect N by supplying N-rich litter. Soil microbial community composition is decided by the tree community.	You et al., 2020
Tropical montane forest	Borneo, Malaysia	Annual temp. Range = 18°C mean annual Precp. = 2714 mm	Dacrydium leaves have a higher concentration of condensed tannins than Lithocarpus leaves and affect the microbial population, activity, and trigger plant-soil feedback mechanisms.	Ushio et al., 2013
Moso bamboo forest	Nantou County, Taiwan	Annual temp. Range = 16.1 – 20.3°C mean annual Precp. = 2250–2600 mm	The SOC dynamics are affected by changes in meteorological circumstances (in particular, temperature). The amount of SOM humification in these bamboo plantings is regulated by altitude.	Wang et al., 2016a
Temperate forest	Tokyo, Japan	Annual temp. Range = 15.5°C mean annual Precp. = 1718 mm	Excess N deposition led to a replacement of air NO_3^- with NO_3^- created by microbes in the organic horizon and the top layer of the mineral soil. The rapid incorporation of atmospheric NO_3^- into the internal microbial N cycle may be attributed in part to microbial activity, namely immobilization and nitrification in organic-rich horizons close to the surface.	Shi et al., 2014
Oak and pine forest	Seoul, Republic of Korea	Annual temp. Range = 11°C mean annual Precp. = 1389 mm	Coniferous pine forests are better able to incorporate fresh C substrates into existing SOC pools than deciduous oak forests in temperate forests.	Park and Ro, 2018
Sub-tropical broad leaf forest	Tiantong National forest park, China	Annual temp. Range = 16.2°C mean annual Precp. = 1374.7 mm	C to N, P and N to P ratios were decreased with soil depth.	Qiao et al., 2020

(Continued)

TABLE 2 (Continued)

Forest type	Area	Climate	Driver of N dynamics/Main findings	References
Spruce and beech forest	Border of Czechia and Germany.	Annual temp. Range = 6.3°C mean annual Precp. = 1000 mm	High-quality litter decomposed irrespective of the acidity and low-quality litter decomposed easily in low-acidity soil. Soil pH decreased up to 0.4 times resulting in less decomposability in both spruce and beech forest.	Růžek et al., 2021
Boreal forest	Ontario, Canada	Annual temp. Range = 0.7°C mean annual Precp. = 889.8 mm	Greater nutrient availability on the forest floor is related to a higher aspen presence, which in turn leads to larger vascular biomass and production in the understory.	Cavard et al., 2011
Sub-tropical forest (coniferous fir and broadleaf)	Fujian, China.	Annual temp. Range = 19.4°C mean annual Precp. = 1731 mm	Soil NH_4^+ -N and NO_3^- -N, notably NO_3^- -N, were reduced due to exogenous C additions. Regardless of the forest soil type, the rate of C amendment had the greatest effect on soil N transformation. Soils with a higher N content may have had a greater decline in N as a result of the addition of exogenous C.	Ma et al., 2019
Temperate forest	Bartın province, Türkiye	Annual temp. Range = 8.9°C mean annual Precp. = 1394 mm	The litter type had the greatest impact on decomposition rates. Fir litter broke down more quickly than beech litter. The microbial biomass of litter increased from summer to autumn.	Kara et al., 2014
Sub-tropical forest (secondary forest)	Sichuan Province, China	Annual temp. Range = 13.9°C mean annual Precp. = 1750 mm	The injection of N enhanced total organic carbon (TOC) in the soil. If more N is added, TOC in topsoils is decreased due to a change in litterfall.	Peng et al., 2020

and provide N to the soil and can modify soil microbial activity, which in turn can affect N availability and transformations in the soil (Leppälammı-Kujansuu et al., 2014; Solly et al., 2014).

Furthermore, it is well-known fact that roots also play a significant role in the nutrient cycles in the ecosystem through interactions between living and dead roots, the amount and quality of the soil structure and nutrients around the roots, and the impact of the roots themselves may vary depending on the soil profile and the quality of the surrounding soil. Ehrenfeld et al. (1997) examined the various impacts of living and dead roots in forest soils and reported that live roots only promoted ammonification rates in mineral soil when an organic surface horizon was present, while dead roots increased the amount of extractable N, but not in the organic matter. It suggests that N dynamics in forest soils are strongly influenced by the presence or absence of an organic horizon in addition to the root activity.

4.2.8. Humidity

Humidity affects N dynamics in forests by influencing plant transpiration and microbial activity, both of which play a role in N cycling through the ecosystem (Dong et al., 2019b). Increased humidity can lead to increased transpiration and microbial activity, leading to a faster rate of N uptake and processing by plants and soil microbes (Luce et al., 2011). However, prolonged higher humidity can also result in decreased plant growth and N uptake due to water stress (Deng et al., 2021). Thus, the effect of humidity on N dynamics in forests is complex and dependent on the specific environmental conditions and time frame considered. It is reported that variation in humidity alters the forest's nutrient and biogeochemical cycles by altering soil temperature. This rise in temperature triggers soil N mineralization rates up to 55% in comparison to the natural forest, with the increase being greatest in the grassland and lowest in the home garden. The concentration

of SOC, MBC, and NO_3^- also decreases in these types of soils in the forests compared to the natural forest (Pandey et al., 2010).

4.2.9. Soil texture

Soil texture also has significant effects on N dynamics in forests. It affects water and nutrient uptake, root growth and distribution, and microbial activity which in turn influences N uptake and cycling (Ma et al., 2016). Fine-textured soils (e.g., clay) have higher water and nutrient-holding capacity but also have lower oxygen levels, which can limit microbial activity and plant root growth (Chivenge et al., 2011). Coarse-textured soils (e.g., sand) have better aeration but lower water and nutrient retention, leading to less efficient N cycling. Soil texture also affects the availability of different forms of N (e.g., NO_3^- , NH_4^+) to plants and microbes, which can influence the rate and efficiency of N cycling as reported by Chivenge et al. (2011) that more N and C were stored in soil aggregates in high clay soils.

5. Significance of N dynamics in forest soils

5.1. Nutrient cycling

Due to higher plant inputs and soil flora and fauna in the forest ecosystem, nutrient cycles, and dynamics change during forest growth and regrowth of the forests and largely depend upon the adequate N supply. In younger forests, mineralization and nitrification are decoupled, i.e., more mineralization and low nitrification, suggesting a closed N cycle that simultaneously preserves N availability for forest renewal (Figueiredo et al., 2019). Moreover, the dynamics of litter decomposition, N cycling, SOM,

and plant-soil interactions may all be altered when trees associate with various mycorrhizas (Eagar et al., 2022).

Sarai et al. (2022) reported that decomposed litter could alter the soil N transformation which may be further impacted by the changes in the structure and function of the soil microbial community. However, this impact is not for all forest types as N-limited boreal forests due to the substantial contribution of understory plants to soil N cycling (Xiao et al., 2022). In addition, soil and plant organic matter breakdowns are crucial to the biogeochemical cycles even in forest settings where understory solar irradiation stays relatively low. Wang et al. (2022d) reported that the litter decomposition in the forest was 64% which increased up to 75% in adjacent areas with less or no tree cover.

5.2. Carbon storage, turnover, and long-term sequestration

The storage of C in forest soils is an important factor in reducing the effects of climate change and global warming through C sequestration. The N enrichment considerably improves C dynamics in forests by an average of 24 and 10%, respectively (Schulte-Uebbing and de Vries, 2018). In subtropical and tropical forests, both the C pool and inputs increased by 10% in response to N addition, the effect was more apparent in boreal forests (+ 17%) than in subtropical forests (−19%). Soil C sequestration was positively affected by N enrichment in boreal (6%) and temperate (7%), but negatively impacted in subtropical (−30%) and tropical (−10%) forests (Ngaba et al., 2022). Similarly, arbuscular and/or ectomycorrhizal trees can modify soil C and N dynamics. Fungi can easily decompose SOM and also form complexes with it. So, the build-up and decomposition of organic materials can occur (Ward et al., 2022). The essential rhizosphere processes of fine root formation, turnover, and breakdown also help in sequestering C in forest soils during succession. Sarai et al. (2022) reported that the fine root turnover contributes more to C turnover than the standing fine root biomass.

The N and C fertilization decreases SOC and N mineralization which is linked to microbial growth and enzyme activity as fertilization was associated with bacterial growth in the high-C larch forest, concluding that N fertilization contributes to soil C sequestration (Na et al., 2022). Soil C sequestration is significantly impacted by plant roots and the mycorrhizal fungi that live in and around them but contributes to SOC build-up. In an ectomycorrhizae-dominated forest with high N addition (25 kg N ha^{−1} year^{−1}), SOC increased from 18.02 to 20.55 mg C g^{−1} (Zhu et al., 2022).

5.3. Forest ecosystem, biodiversity, and soil health maintenance

As an indicator of healthy soil, SOC levels are often used for this purpose. To better understand soil functioning as a major element for C sequestration along agricultural production and food and water security. Substantial SOC accumulation in forest soils was agreed upon, providing not just a C sink but also its supply, despite

limited data availability and large observed fluctuation in SOC content (Alavi-Murillo et al., 2022). The high rates of SOM/SOC formation play a major role in ecosystem stability (Siwach et al., 2021).

6. Role of forest type in determining the soil physicochemical and biological properties

6.1. Physico-chemical properties

After latitude and altitude, the physicochemical and biological properties of soil may also have a role in forest and tree species distribution. Alternatively, soil formation and associated edaphic qualities may also be affected by variations in tree species composition. The pace at which chemical weathering of parental material occurs, which affects pH and the composition of complex organic acids in soil solutions, might vary with tree species. However, trees mostly influence soil minerals weathering in the top few inches of soil or close to the roots (Joshi and Garkoti, 2021). Some tree-soil interactions, including the interception of airborne contaminants or the podzolization of soil, may have evolved with just a weak or no correlation to plant fitness or closeness. In addition, local factors like litter input, stand species composition, and microclimate variables can have an impact on the chemical properties of forest soils, while long-term effects (like permanent vegetation over a long period) or drastic alterations (like fires, intensive harvesting) primarily influence soil structure and its physical properties (Toro-Manriquez et al., 2019; Joshi and Garkoti, 2021).

6.2. Biological properties

One of the most important aspects of the biological health of the soil is bacterial community (Ao et al., 2022). Changes in the microbial biomass of soil are a good indication of the ongoing transformations in the soil nutrients and properties. Knowing how the microbial biomass in plantation soil fluctuates over time is crucial for effective plantation management and cultivation.

It is reported that nutrients serve as useful markers of how forest management methods affect the dynamics of SOC. The largest C:N levels were seen in the autumn and the smallest values were observed in the winter for the three different forest types, although these seasonal patterns were not consistent (Babur et al., 2021). Sun Y. et al. (2021) reported that the rhizosphere's microbial biomass nitrogen (MBN) was more responsive to mulching and other soil environmental changes. Soil P was shown to correlate with TN and dissolved N, although other N fractions were significantly influenced by soil physical qualities (temperature, water content, bulk density) (Yin et al., 2021). The N content of both fine roots and organic mulch was reduced by mulching, although the N content of the soil was more closely connected to the N content of the leaves (except MBN) (Wang H. et al., 2019; Table 3).

TABLE 3 Influence of N dynamics on soil properties of different forest ecosystems.

Area	Forest type	Climate	Major influencing factor	Effects on soil properties/Main findings		References
				Physico-chemical	Biological	
Uttarakhand, India	Oak and pine forest	Annual temp. Range = 23–24.22°C mean annual Precp. = 128–144.10 mm	Forest fires induced more carbon resources.	Soil pH was increased by 0.78 units higher. EC and TN were increased but soil moisture was reduced.	The increase in MBC was 63 and 40% in the oak and pine forests, respectively. DHA activity was enhanced, while ACP activity was reduced.	Singh et al., 2021
Guiyang City, China	Pinus massoniana forest	Annual temp. Range = 15.2°C mean annual Precp. = 1199 mm	Temporal (10–60 years) effects of pinus forest soils.	Available N, P, K, C:N, C:P, N:P, bulk density, and soil moisture increased with time.	SOC increased with time but decreased with soil depth.	Yin et al., 2021
Lvliang City, China	Pine forests	Annual temp. Range = 4.2°C mean annual Precp. = 822.6 mm	Higher plant density.	–	qMBC and N increased but decreased with higher stand density, C:N showed an opposite trend.	Zhang et al., 2021
Iran	Temperate forest	Annual temp. Range = 15.5°C mean annual Precp. = 808 mm	Tree diversity increases and changes the natural cover of the plantation.	NPK concentrations decreased.	Acid phosphatase, arylsulphatase, and invertase activities decreased but urease activity increased in the topsoil. MBN, mineral nitrogen mineralization increased.	Kooch et al., 2018
Fujian Province, China	Fir forest	Annual temp. Range = 20°C mean annual Precp. = 1650 mm	Forest conversion.	pH, BD and $\text{NH}_4^+ \text{-N}$ increased. SOC, AP, TN, $\text{NO}_3^- \text{-N}$, $\text{NH}_4^+ \text{-N}$, MBC, MBN.	Fungal diversity declined. C, N, and P-cycling decreased.	Guo et al., 2022
Yunnan, China	Tropical forest	Annual temp. Range = 21.5°C mean annual Precp. = 1557 mm	Ant's nesting effects on microbial carbon and physicochemical properties.	Low BD, higher soil temp. and moisture.	Up to 172.7% MC, TOC 75.5% TOC, 180.6% ROC, 129.5% TN, and 2.8% increase in NO_3^- was observed.	Wang H. et al., 2019
Minnesota, United States	Hardwood forest	–	Earthworm abundance.	Reduced nitrification in presence of earthworms.	Bacteria and fungi were found maximum near the soil surface. Denitrification and N fixation increased.	Jang et al., 2022
Daxing'an Mountains, China	Boreal forest	Annual temp. Range = -4.9°C mean annual Precp. = 430–550 mm	Forest succession.	Increase in soil moisture at later stages of succession. Soil $\text{NO}_3^- \text{-N}$ was higher later but $\text{NH}_4^+ \text{-N}$ was high at the early and intermediate stages. MBC and MBN were high at later stages. CH_4 and N_2O emissions were greater than CO_2 .	–	Duan et al., 2022
Guangxi Zhuang Autonomous Region, China	Karst forest	Annual temp. Range = 19.9°C mean annual Precp. = 1571.1 mm	Restoration of vegetation.	Soil pH decreased but SOC and NPK increased.	Urease activity was enhanced with microbial diversity.	Lu et al., 2022
Heilongjiang Province, China	Temperate forest	Annual temp. Range = 2.8°C mean annual Precp. = 700 mm	Comparison of monoculture and mixed plantation effects on soil properties.	Less or no effects were noted on C and N dynamics.	Mixed-species plantations can significantly enhance soil available N and exo-glucanase, β -glucosidase, and N-acetyl- β -glucosaminidase activity levels. Microbial community functions were altered.	Yang et al., 2022

7. N dynamics in broadleaf and Moso bamboo forest soils

Soil quality and nutrient storage in forests are interlinked. Although there are minute differences between the broadleaf and bamboo forests according to their respective ecosystem functioning, there are some significant differences that exist and are highlighted in [Figure 3](#). [Feng et al. \(2020\)](#) reported that litter decomposition has a profound effect on N dynamics, and this effect varies greatly with the variety of tree species present in a given forest. [Wang et al. \(2018\)](#) studied the effects of litter mixing and altering the stand environment on the litter decomposition rate and the composition-specific litter organic C and N loss rate of a mixed-species plantation. Mixed-species plantations with lower-quality litter reduced decomposition and resisted N and C loss, whereas higher-quality litter speeded up litter decomposition, which was caused by the higher SOM and SON availability in the mixed-species plantation.

It has been reported that tree C, N, and P stocks all fell when moso bamboo and broadleaf forests are converted to other types of forests, with declines of 43.8, 47.9, and 63.1%, respectively, while C and N stocks throughout the whole soil profile fell by 19.1 and 13.0%, respectively as conversion resulted in a decrease in soil P stock from 0 to 20 cm. It indicates that tree biomass can drive the N dynamics and retention of nutrients. In forest soils, the metabolism of C and N is also influenced by the microbial communities and enzyme activities present there. Soil pH, MBC, MBN, C, N, P, NH_4^+ -N, and NO_3^- -N levels were all shown to be strongly impacted by forest type ([Ji et al., 2021](#)). Moreover, trees with arbuscular mycorrhizae vary from ecto- and endomycorrhizal tree species in their litter quality and N cycle patterns, which may influence mycorrhizal colonization and the community's composition and variety ([Zhang et al., 2022](#)). [Figure 4](#) explains the factors and processes taking place in broadleaf and bamboo forest ecosystems during N cycling/dynamics. Soil P, calcium (Ca^+), K, and magnesium (Mg^+), as well as elemental stoichiometric ratios also respond differently in broadleaf and bamboo forests ([Feng et al., 2017](#)).

7.1. Significance

The ecology, as well as the N dynamics in forest soil, is distinct from that of the other soil ecosystems. Nutrient and biogeochemical cycles are necessary for the proper functioning of the forest ecosystem like moso bamboo forests. Moreover, for proper functioning nutrient cycles must work and govern properly. These cycles are run by input factors, i.e., natural, and human processes that affect litter formation and decomposition. The growing influences of different natural and human variables on the nutrient and biogeochemical cycle of tropical forest ecosystems highlight the significance of studying C, N dynamics, litter formation, and its breakdown processes. As the soil microbiome plays a vital role in the feedback between the nutrient cycle and the climate, models used to anticipate changes in ecosystem functioning under changing climatic scenarios must account for this variation among plant species ([Xu et al., 2018](#)). As a result of the

increase in plant resources and the subsequent rise in soil enzyme activities, soil C, and accessible N, P, and K levels are all enhanced.

8. Factors affecting C and N dynamics in broadleaf and Moso bamboo forests

8.1. Soil properties

Moso bamboo and broadleaf forests have a high SOC storage capacity but also great geographic variation. The SOC in both forest types was shown to be significantly linked with BD ($R^2 = 0.373$), pH ($R^2 = 0.429$), GC ($R^2 = 0.163$), and CEC ($R^2 = 0.263$) ([Zhang et al., 2015](#)). Another study revealed that SOC, its fractions, C mineralization rate, soil pH, and total N in 0–20 and 20–40 cm soil layers rose dramatically with increasing duration of intensive management, along with improvements in aggregate stability ([Yang et al., 2021](#)). A study in bamboo plantations revealed that SOC, labile soil organic C pools, TN, water-soluble organic N, NH_4^+ -N, NO_3^- -N, total P, organic and inorganic P content in the rhizosphere are all significantly increased ([Ni et al., 2021](#)). In another study, soil samples from the moso bamboo forest were collected at depths of 0, 20, and 60 cm at 138 different spots around the research region. The N, P, and K concentrations varied from 1.01 to 4.11 g kg^{-1} , 0.025 to 0.131 g kg^{-1} , and 0.42 to 5.40 g kg^{-1} , respectively ([Guan et al., 2017](#); [Xiao et al., 2021](#)).

8.2. Litterfall

The effects of N deposition and management practices on leaf litterfall and N and P return in the moso bamboo (*P. edulis*) forest are not yet known. However, [Zhang et al. \(2017\)](#) studied the variations between no N, low N (N30), medium N (N60), and high N (N90) levels of simulated N deposition, as well as the control with no N. It was concluded that between 78% and 82% of annual leaf litterfall, 86–94% of annual N return, and 85.6–96% of annual P return occurred during the study period.

8.3. N addition

Same as the other forests ecosystem, N addition in the bamboo forests also results in more stable N and C concentrations and efficient biogeochemical cycling. [Li Y. et al. \(2021\)](#) studied the changes in soil microbial abundance, variety, and community structure in response to N addition (0, 30, 60, or 90 $\text{kg N ha}^{-1} \text{ year}^{-1}$) in a moso bamboo (*P. edulis*) forest in subtropical China. Results showed an increase in microbial biodiversity ([Lv et al., 2022](#)). A 7-year field experiment was conducted in a subtropical moso bamboo (*P. edulis*) plantation in Zhejiang Province, China to examine the effects of varying N addition rates (0, 30, 60, and 90 $\text{kg N ha}^{-1} \text{ year}^{-1}$) on soil respiration rates with stumps of three ages (1, 3, and 5 years after cutting). Results indicated that N addition reduced soil respiration by 4.69 to 27.37% compared to the control treatment ([Cai et al., 2021](#); [Li et al., 2022](#)).

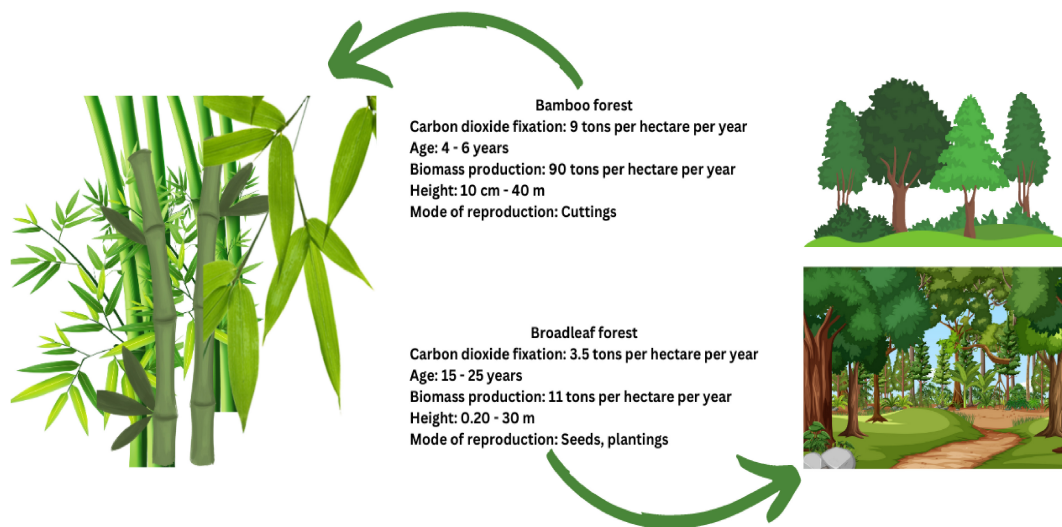


FIGURE 3 Differences in the bamboo and broadleaf forest species.

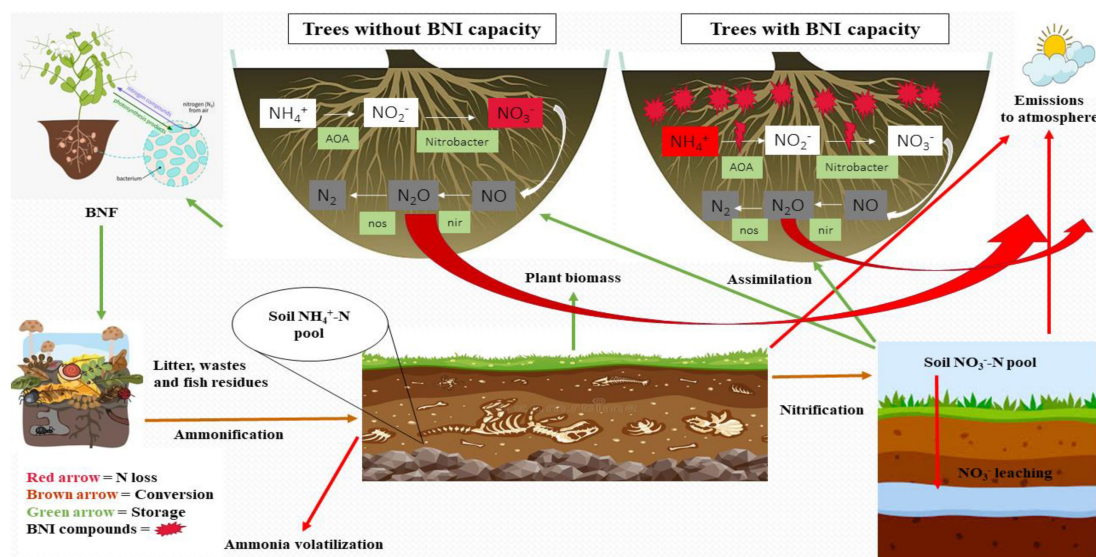


FIGURE 4 Nitrogen dynamics under the direct influence of trees with and without BNI capacity.

8.4. Stress factors

The C and N cycle of the forest ecosystem, i.e., moso bamboo forests could be greatly impacted by increases in environmental stresses, such as drought frequency and severity. In a simulated study involving drought as a stress factor, three different litterfall treatments were tested for responses about soil respiration, temperature sensitivity, and the lagging effect of the soil. The treatments were ambient litterfall, litter addition, and litter removal. It was also noted that the annual soil respiration rate was lower in the unchanged treatment ($2.34 \text{ mmol m}^{-2}\text{s}^{-1}$) compared to the control ($3.15 \text{ mmol m}^{-2}\text{s}^{-1}$) (Ge et al., 2018). Soil respiration's temperature sensitivity was lowered by 8.4% due to drought, 15.4% due to litter addition, and 7.6% due to litter removal

(Ge et al., 2018). It was also reported that drought reduces litter decomposition rates by up to 30%, thereby affecting N dynamics (Jin et al., 2020; Tong et al., 2020; Ge et al., 2022).

9. Conclusion and future prospects

Forest ecosystems play a crucial role in global C and N cycles, as well as temperature and precipitation patterns. Hence, they are the focus of study by scientists from all over the world. Because of the worldwide goals of carbon neutrality and carbon sequestration. They constitute an essential component of the global carbon sink, i.e., moso bamboo forests. Moso bamboo and broadleaf forests are crucial elements of the carbon and N cycles since they are so

prevalent in the subtropics. Because it is essential to have clear quantification of changes in bamboo forest soil to understand the N dynamics of bamboo forests, soil C sequestration, N dynamics, and the biomass of the entire broadleaf and moso bamboo forest ecosystem. Moreover, C and N dynamics are greatly influenced by biotic and abiotic factors. Even small changes in these factors can cause severe negative impacts on soil biogeochemical cycles and disturbance in soil ecology, ultimately destroying balance in an ecosystem. More and improved research on soil microbes and microbial residues is needed to understand the mechanisms of soil microbial responses to different settings and the carbon and nitrogen cycle and sequestration process for C and N accumulation by microbial residues in broadleaf and moso bamboo forests.

Author contributions

MS: conceptualization and original draft writing. YL: funding acquisition. FY, ZF, and YL: visualization and revision. MS, FY, and

YL: original draft review and funding acquisition. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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