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Litter nutrient dynamics under different tree plantations of humid subtropical region of Uttarakhand, India

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Abstract Litter plays a vital role in forest ecosystems, significantly contributing to nutrient cycling through litter production and decomposition. Understanding these processes is crucial for forest management and conservation, especially in the face of global environmental changes. This research is important because it provides insights into the litterfall patterns and nutrient dynamics of different tree species, which are essential for maintaining forest health and productivity. The present study aimed to determine the quantity and pattern of litterfall and nutrient return to the forest floor of *Pinus roxburghii*, *Shorea robusta*, and *Bambusa tulda*. We collected litterfall monthly over two years in three different plantations of *P. roxburghii*, *S. robusta*, and *B. tulda*, and measured the nutrient content of the litter. The mean annual litter production recorded in these plantations was greatest in *B. tulda* (4652.15 kg $ha^{-1}yr^{-1}$), followed by *S. robusta* (3731.4 kg $ha^{-1}yr^{-1}$) and *P. roxburghii* (2588.85 kg $ha^{-1}yr^{-1}$). The plantations included both the main species and associated understory vegetation, such as herbs and shrubs. Leaf litter from the main species accounted for the highest total litterfall in April. During this period, leaf litter accounted for approximately 24% of the total in *S. robusta*, 16% in *P. roxburghii*, and 15% in *B. tulda*. Minimum mean monthly litterfall was recorded in September and November for *P. roxburghii* and *S. robusta*, and in November and December for *B. tulda*. There was significant monthly variation in nutrient content between the species. Maximum nitrogen (N) was measured during June for *P. roxburghii*, December for *S. robusta*, and January for *B. tulda*, and phosphorus (P) and potassium (K) concentrations also varied significantly. Annual patterns of nutrient return followed the order N > K > P. Maximum nutrient return was observed during April in all species due to higher litter production during that month. There was greater variability in litter quality in the broadleaved forest (*S. robusta*) than in the coniferous forest (*P. roxburghii*), indicating the more dynamic functioning of broad-leaved plantations compared to coniferous ones.. This research highlights the critical role of litterfall in nutrient cycling within forest ecosystems and underscores the importance of considering species-specific litter dynamics in forest management and conservation strategies.

Keywords: litter dynamics, nutrient return, *Pinus roxburghii*, *Shorea robusta*, *Bambusa tulda*.

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Introduction

Forests are complex biological and physical systems with high inter-dependency among their biotic and abiotic components. The forest ecosystem is the basic ecological unit for energy processing and nutrient cycling, influencing agriculture, hydrology, and micro-climate (Brockerhoff et al. 2017). Trees improve the nutrient status of soils in forest ecosystems through erosion control (Elliot et al. 2018), the addition of organic matter via litter deposition (Wrightson et al. 2024), water conservation, protection of water catchment areas (Kumar et al. 2024), and creation of balanced micro-climatic conditions within an ecosystem (Horváth et al. 2023). Litterfall is an essential pathway for the flow of organic matter and nutrients from vegetation back to the soil, making it a necessary energy and biogeochemical cycling component in the forests (Krishna & Mohan 2017). This pathway requires detailed investigations, which involve comprehensive ecological studies of forest litter dynamics through systematic monitoring and analysis of litter production, nutrient return, and decomposition (Panwar & Gupta 2015).

In addition to high levels of leaf litter production, forest ecosystems provide a range of other related values such as biodiversity conservation, carbon sequestration, soil stabilization, water regulation, and habitat provision (Brockerhoff et al. 2017). These functions are essential for maintaining ecological balance and supporting a wide variety of plant and animal life. Leaf litter production in forests depends on the availability of nutrients as well as the pattern and rate of nutrient uptake by plant and tree species occurring in the forest (Maxwell et al. 2022). Trees take up large quantities of nutrients from the soil, and a high proportion of these are returned to the soil through litterfall. Many nutrients are also removed when trees are harvested (Zhu et al. 2022). The organic matter in forest floor vegetation acts as a nutrient reservoir for intra-system cycling and regulates forest hydrology (Takahashi 2021). Habitat conservation involves identifying critical habitats, implementing conservation measures, monitoring and assessing the effectiveness of these actions, and adapting strategies based on findings. The litter on the forest floor represents an essential stage in habitat conservation, as it contributes to nutrient cycling and soil health, ensuring the sustained resilience of the ecosystem (Giweta 2020). Studies on litterfall in forests of major climatic zones, including tropical, temperate, boreal, and Mediterranean, have been published by many authors (Jia et al. 2016; Ahirwal et al. 2021; Wang et al. 2021); however, little has been published on litterfall dynamics in planted forests, which this study aims to address.

Through litterfall and subsequent mineralization, nutrients are re-assimilated by plant roots and contribute to plant nutrition. Hence, litterfall is a dynamic and essential component of nutrient cycling in the ecosystem (González et al. 2022). Above all, studies on the continuous flow of nutrients and energy through the ecosystem, a vital characteristic of ecosystem function, are essentially required. An ecosystem has a richly detailed budget of inputs and outputs; however, it is difficult to assess the impact of human activities on landscapes of the biosphere due to a lack of precise information about these inputs and outputs. Therefore, the study of nutrient flow in an ecosystem becomes an important research area because it can provide a basic understanding of the nutrient fluxes in a unique ecosystem, enabling us to understand the biogeochemical cycling of the plantation forestry. This study aims to evaluate nutrient dynamics in different plantation types within humid subtropical ecosystems, focusing on *Pinus roxburghii* (coniferous), *Shorea robusta* (broadleaved), and *Bambusa tulda* (bamboo), and to compare patterns of nutrient flow and litter production among these plantation types to understand their role in nutrient cycling. *Pinus roxburghii*, *Shorea robusta*, and *Bambusa tulda* were chosen due to their ecological and economic importance in the region. *Pinus roxburghii*, a dominant conifer in the subtropical Himalayan forests, is crucial for timber production and soil stabilization. *Shorea robusta*, a prominent broadleaved species, is valued for its hardwood and plays a significant role in biodiversity conservation. *Bambusa tulda*, a fast-growing bamboo species, is essential for local economies and ecosystem services. The specific objectives are to quantify litterfall and nutrient return to the forest floor for each plantation type over a specified period, analyze monthly and seasonal variations in nutrient concentrations i.e., nitrogen (N), phosphorus (P) and potassium (K), assess the impact of different plantation types on overall nutrient changes and compare nutrient dynamics between coniferous, broadleaved, and bamboo plantations to identify species-specific influences on biogeochemical processes. The hypotheses guiding this study are that (1) there will be significant differences in litterfall quantities and nutrient return rates among the different plantation types due to their distinct physiological and ecological characteristics; and (2) that nutrient concentrations in the litter will exhibit significant monthly and seasonal variations, with distinct patterns for each plantation type. To test these hypotheses, we collected litterfall monthly for two years in three contrasting humid subtropical plantations and analysed their nutrient contents and return.

Materials and Methods

Study site and climate

The experimental area was selected in the Western Sub-Division of Dehradun, India, located between 30.3458630°N to 30.3337510°N and 78.0010170°E to 78.0097190°E (Universal Transverse Mercator Zone: 44R) at an elevation of 653 meters. The *Pinus roxburghii*, *Shorea robusta,* and *Bambusa tulda* were planted during 1925, 1924, and 1932, respectively, in the New Forest Estate and thus attained the age of 96, 95, and 89 years, respectively. The estate's status was barren land before the establishment of these plantations, with native shrubs and herbs. The experimental area was subdivided into five sections of 1.6 ha each. Five sampling points were selected randomly in each plantation for the systematic collection of litter samples. From each sampling point, litter samples were collected every month for two years (2016-2018). The climate of the study area is humid sub-tropical and mainly receives precipitation during the monsoon (July to September) and winter seasons (December to February). Total rainfall during the first year was 1931.50 mm, with a maximum of 607.60 mm in August. In the second year, maximum rainfall of 810.00 mm was also received in August, with total annual rainfall of 2160.70 mm. The monthly mean minimum temperature recorded for the study area was 11.90°C in January, whereas the monthly mean maximum temperature was 27.00°C in June (Fig. 1).

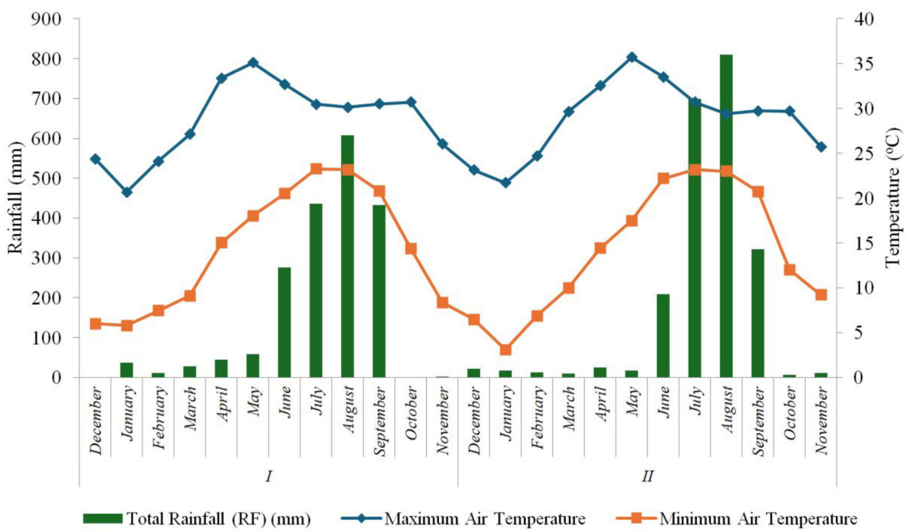

Figure 1 Variation in air temperature and rainfall over two years (2016-2018) in the study area.

The *P. roxburghii* plantation has a density of 950.00 trees ha^{-1}, a basal area of 19.00 $m^2 ha^{-1}$, a tree diversity (Shannon Wiener Index) of 1.51, and an Importance Value Index (IVI) of 198.50 (Sivaranjani & Panwar, 2020). Seven shrub species (*Lantana camara*, *Solanum indicum*, *Clerodendrum thomsoniae*, *Murraya koenigii*, *Rubus niveus*, *Plumeria rubra*, *Maclura cochinchinensis,* and *Flacourtia indica*) were present in the *P. roxburghii* plantation with a density of 72.22 individuals 100 m^{-2}. Herbaceous species included *Oplismenus compositus*, *Ageratum conyzoides, Achyranthes aspera*, *Eupatorium adenophorum,* and *Clematis gouriana,* at a density of 3.20 individuals m^{-2}. In the *S. robusta* plantation, tree density was 1073.00 individuals ha^{-1}, basal area 51 $m^2 ha^{-1}$, tree diversity 1.68, and IVI 169.07. Additionally, five shrub species (*Clerodendrum infortunatum*, *Jasminum multiflorum, Maclura cochinchinensis, Vallaris solanacea* (Climber), and *Coffea benghalensis*) were recorded with a density of 42.22 individuals 100 m^{-2}. No herbaceous species were identified under *S. robusta*. The *B. tulda* plantation had a density of 1000 individuals ha^{-1}, basal area of 265.96 $m^2 ha^{-1}$ and IVI of 300, and no shrub or herb species were identified (Sivaranjani & Panwar 2020).

Litter collection, processing and analysis

The litter samples were collected monthly from a 2 x 2 m randomly selected plot at each plantation. The collected litter was oven dried at 80 ± 2°C until a constant weight was reached. The dried litter samples were ground using a Wiley Mill for chemical analysis. Stock solutions were prepared from ground-litter fractions by the Triacid Digestion Method (nitric acid (10 ml, 69-70%), perchloric acid (4 ml, 70%), and sulphuric acid (1 ml, 98%)) following Misra (1968). The Kjeldahl method was used to measure N (Singh et al. 2013), using the Kjeltec Auto-1030 Analyzer (Hillerod, Denmark). P in litter samples was conducted using a spectrophotometer (Kyoto, Japan). K analysis was performed using a flame photometer (Singh et al. 2013). P and K in the litter samples were measured using an Atomic Absorption Spectrophotometer - Spectra AA-10/20 (Palo Alto, California). To calculate the nutrient return, total and individual nutrient concentrations were measured from ground-litter fractions using the Triacid Digestion Method.

Statistical analysis

Statistical analysis was conducted using IBM-SPSS, Inc.'s (Chicago, IL, USA) SPSS 21. The following hypotheses were formulated:

H_o: $\mu_B = \mu_C = \mu_S$

H_i: $\mu_B \neq \mu_C \neq \mu_S$

The null hypothesis (H_o) states that there would be no significant differences in litter production, nutrient return, and nutrient concentration between the different plantation types, namely *Bambusa tulda*, *Shorea robusta*, and *Pinus roxburghii*. We tested our alternative hypothesis (H_i) that there are significant differences at the 0.05 level. Where μ_B, μ_C and μ_S represent the mean values for species *Bambusa tulda*, *Pinus roxburghii*, and *Shorea robusta*, respectively. To quantify these monthly and seasonal variations, an Analysis of Variance (ANOVA) test was conducted to compare litterfall, nutrient concentration, and nutrient return across the months for each species.

Results

Litter production under different plantations

The mean monthly average of the two-year data indicated that maximum litter production occurred in April. For *P. roxburghii*, peak litter production was 407.80±18.70 kg ha^{-1}, contributing 15.75% to the total annual litter production. In *S. robusta*, the maximum litterfall was 887.00±117.50 kg ha^{-1}, accounting for 23.77% of the total litter production. Similarly, *B. tulda* produced 713.80±159.00 kg ha^{-1} litter, contributing 15.34% to the total litter (Fig. 2). Minimum litter production was recorded in September for *P. roxburghii* and *S. robusta*, with values of 115.75±14.05 kg ha^{-1} and 61.40±2.00 kg ha^{-1}, respectively, while for *B. tulda*, the minimum was observed in December at 185.45±75.55 kg ha^{-1}. During these months of minimum litterfall, the contributions to total litter production were 1.65%, 4.47%, and 3.99% for *P. roxburghii*, *S. robusta*, and *B. tulda*, respectively (Figure 2). The average annual litter production for the different plantation types was 2588.85 kg ha⁻¹ for *P. roxburghii*, 3781.40 kg ha⁻¹ for *S. robusta*, and 4652.15 kg ha⁻¹ for *B. tulda* plantations. Post-hoc Tukey's HSD tests confirmed that the peak litterfall in April was significantly higher than the litterfall in the months with the lowest values, validating the observed seasonal patterns in litter production.

Litterfall exhibited significant monthly variation across the different plantation types. For *P. roxburghii*, the ANOVA results indicated significant differences in litterfall between months ($F= 14.74$, $p= 0.000$). Post-hoc Tukey's HSD tests identified specific differences between months, revealing that maximum litterfall values of 426.50±71.73 kg ha⁻¹ and 389.10±103.62 kg ha⁻¹ recorded in April were significantly higher than the minimum values of 129.80±39.14 kg ha⁻¹ and 80.00±16.87 kg ha⁻¹ observed in September and November, respectively (Figure 3). Similarly, for *S. robusta*, the ANOVA showed significant monthly differences in litterfall ($F = 60.70$, $p = 0.001$). Tukey's HSD tests indicated that the peak litterfall of 769.50±52.70 kg ha⁻¹ and 1004.50±75.52 kg ha⁻¹ in April was significantly greater than the minimum values of 63.40±22.23 kg ha⁻¹ and 45.60±9.18 kg ha⁻¹ in September and November, respectively (Figure 3). In *B. tulda*, the ANOVA also confirmed significant monthly variations in litterfall ($F = 20.78$, $p < 0.001$). Post-hoc tests revealed that the highest litterfall values of 554.80±24.00 kg ha⁻¹ and 880.20±32.00 kg ha⁻¹ in April and February were significantly different from the lowest values of 109.90±40.99 kg ha⁻¹ and 89.90±15.08 kg ha⁻¹ recorded in December and November, respectively (Fig. 3). These analyses demonstrate that the variations in litterfall across the months are significant, highlighting the distinct seasonal patterns in litter production for each species.

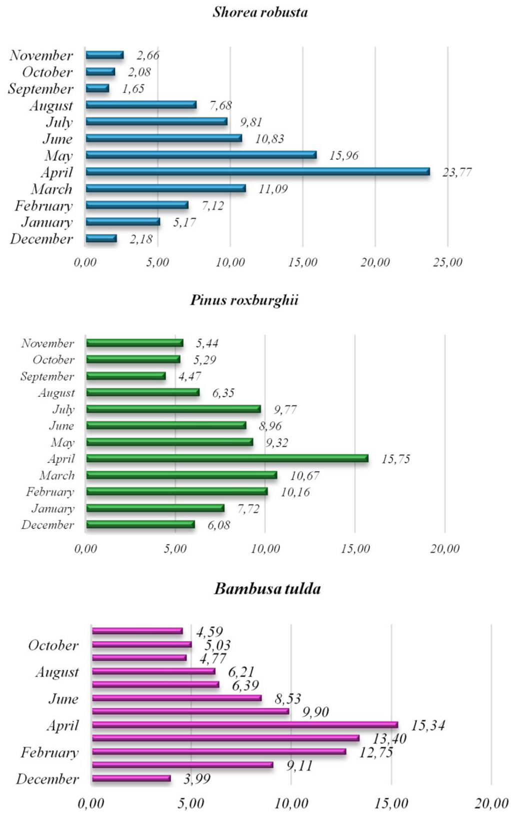

Figure 2 Monthly contribution (%) of main plantation species to total litterfall in the study area.

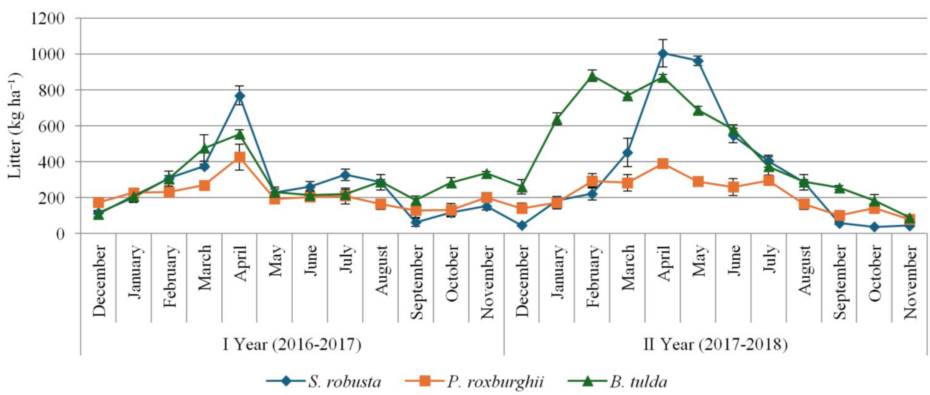

Figure 3 Annual pattern of litterfall production under different plantations in the study area (n= 5).

Litter collection, processing and analysis

To evaluate the nutrient content in the litter, we conducted a comprehensive analysis using monthly collected samples across different plantation types, followed by statistical tests to assess significant variations. In *S. robusta*, the concentrations of all nutrients (N, P, and K) were significantly different (F: 5.484, p = 0.0001) when compared across different months. Similarly, in *P. roxburghii*, N and K concentrations showed significant differences (F: 2.882, p = 0.006) across months. In contrast, the N (F: 1.958, p = 0.054) and P (F: 1.139, p = 0.376) concentrations in *B. tulda* did not exhibit significant differences among months, although K (F: 9.736, p = 0.000) concentrations were significantly different across months. The average N concentrations observed among the different species were 1.22±0.03% for *P. roxburghii*, 0.82±0.02% for *S. robusta*, and 0.84±0.03% for *B. tulda*. The average P concentrations were 0.03±0.001% for *P. roxburghii*, 0.04±0.003% for *S. robusta*, and 0.02±0.0008% for *B. tulda*. The P content was significantly different for *S. robusta* (F:4.279, p = 0.000). K content showed annual mean values of 0.46±0.03%, 0.49±0.02%, and 0.49±0.05% for *P. roxburghii* (F:2.749, p =0.008), *S. robusta* (F:5.482, p = 0.000), and *B. tulda* (F:9.736, p = 0.000), respectively, with significant differences observed across the species. The nutrient content in the litter samples varied significantly over the study period, highlighting the influence of seasonal and species-specific factors on nutrient dynamics. The monthly variation in nutrient concentration is shown in Fig. 4.

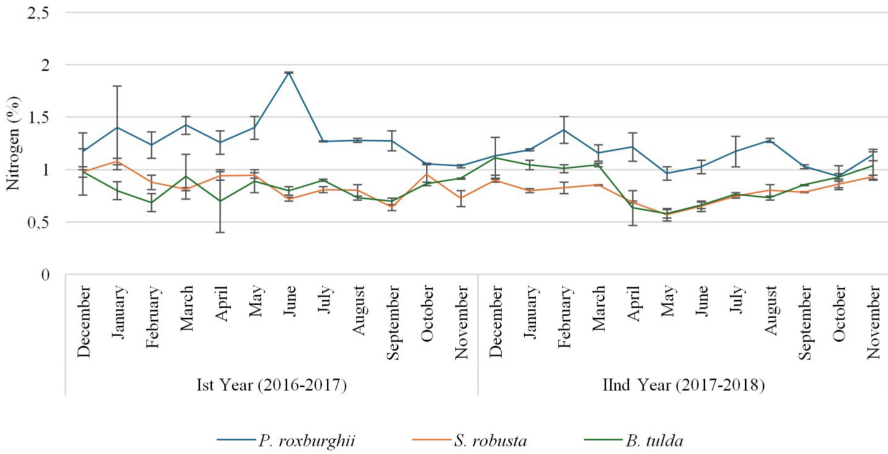

Figure 4a Monthly nitrogen concentrations (%) in litter under different plantations.

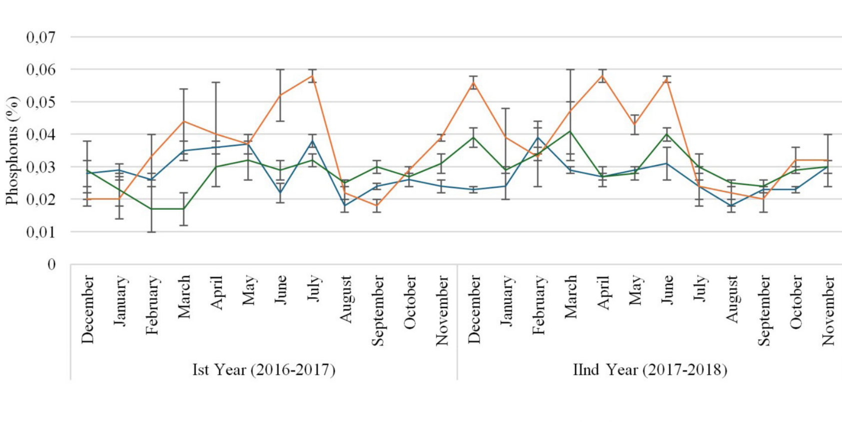

Figure 4b Monthly phosphorus concentrations (%) in litter under different plantations.

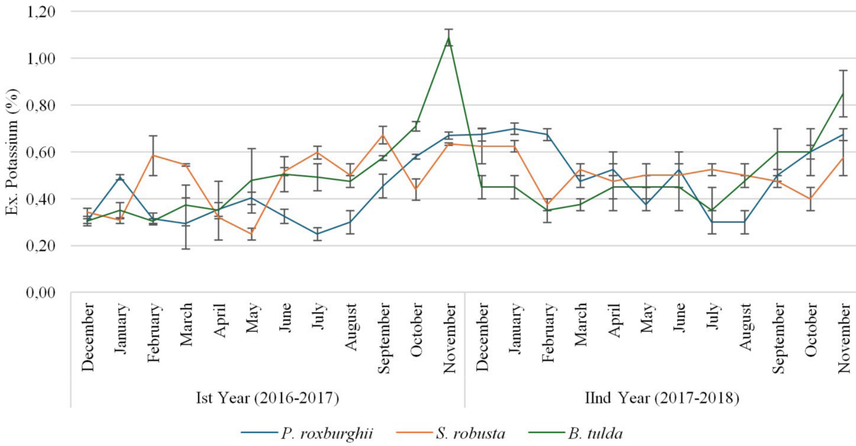

Figure 4c Monthly potassium concentrations (%) in litter under different plantations.

Nutrient return

The total nutrient return was obtained in the order N > K > P in all plantations. However, individually N return was higher in *B. tulda,* followed by *P. roxburghii* and *S. robusta.* The total annual N return was 31.94±1.90 kg ha^{-1} in *P. roxburghii*, 29.03±1.07 kg ha^{-1} in *S. robusta*, and 38.78±10.89 kg ha^{-1} in *B. tulda*. Specifically, the N return was significantly different within *Shorea robusta* (F: 9.341, p =0.000) and *Pinus roxburghii* (F: 7.688, p = 0.000), indicating notable variation in N return among these species. In contrast, the N return for *Bambusa tulda* was not significant (F: 1.08, p = 0.01), suggesting minimal variation in N return for this species. N return was significantly different for April in *S. robusta* and *P. roxburghii* plantations. Similarly, P return was also significantly different for *S. robusta* (F: 3.478, p = 0.000) and *P. roxburghii* (F: 5.323, p = 0.000). P return under different plantations was 0.74±0.02 kg ha^{-1} in *P. roxburghii,* 1.55±0.33 kg ha^{-1} in *S. robusta* and 1.39±0.49 kg ha^{-1} in *B. tulda*. The results indicated that more of the P was returned on the forest floor in the stand of *S. robusta*. Average annual values of K return calculated as above show 11.56±1.69 kg ha^{-1} in *P. roxburghii*, 17.89±3.33 kg ha^{-1} in *S. robusta* and 21.44±4.30 kg ha^{-1} in *B. tulda*. However, no significant differences in K return were found in all plantations.

Discussion

Litter production

Leaf litter is a significant source of soil nutrients (Alvafritz & Hertel 2024), playing a crucial role in nutrient cycling and energy transfer within forest ecosystems (Bellingham et al. 2013, Sayer et al. 2020). Assessing litterfall production and nutrient return is vital for understanding nutrient cycling, forest growth, carbon fluxes, and interactions with environmental variables (Liu et al. 2024) and, subsequently, informing forest management practices (Guo et al. 2006). In this study, total annual litter production varied across different plantations, with *B. tulda* exhibiting the highest production, followed by *S. robusta* and *P. roxburghii*. The variation in litter production among forest types was influenced by species richness and changes in tree density, with different biotic and abiotic factors contributing to distinct litterfall components. Kumar and Tewari (2015) also reported peak litterfall during April, May, and September in *P. roxburghii* plantations. Giweta (2020) showed that litter production appears to be little affected by differences in plant density within closed-canopy forests.

In the present study, *P. roxburghii*, *S. robusta*, and *B. tulda* exhibited marked variations in litterfall across different months and seasons. Notably, lower litterfall was observed in the first year, potentially due to reduced rainfall compared to the second year. Water stress may have accelerated litterfall or correlated with increased plantation biomass, particularly in bamboo. Similar micro-level variations have been observed in beech and pine stands in Mediterranean climates in Spain (Zhu et al. 2021).

On monthly basis, the maximum litterfall occurred in April for all species, while the minimum litterfall was recorded in September for *P. roxburghii* and *S. robusta*, and December for *B. tulda*. Zhu et al. (2019) also noted peak litterfall during cool and dry seasons. The March-April leaf-fall peak in all species may be attributed to the prevailing drier climate during this period (Pérez et al. 2022).

P. roxburghii is an evergreen species with year-round litterfall. Higher litterfall accumulated during April-May during warm and drier conditions prevailing during the study (Jugran & Tewari 2022). Leaf litterfall was observed during the most humid and rainy months in the present study for all the species studied, as Navarro et al. (2013) reported earlier. They observed minimum leaf fall in wet years in Scots pine stands in Germany. *S. robusta* occurs mainly in moist deciduous and evergreen forests on the southern slopes of the Himalayas. Das & Mondal (2015) reported the highest litterfall during April and reported that annual litter production increased with the age of the plantation. Litterfall varied seasonally; the maximum litterfall was recorded in the dry period in the wet period (Kumar et al. 2010, Devi & Yadava 2010).

In comparison with deciduous trees, bamboo leaf emerges once every two years rather than every year. Therefore, the accumulation, transformation, and consumption of synthetic nutrients occur in a two-year cycle. Generally, there are two peaks observed every year. The first peak occurs in spring (April-May), and the second peak in late autumn (November), as reported by the previous studies (Zheng et al. 2022). Leaf fall was highly correlated with the daily mean air temperature and rainfall from the previous month. A greater amount of leaf litter was associated with less rainfall and higher air temperature. Sometimes, small peaks were observed during the transition period of the dry season from February to April. These findings were in accordance with Wu et al. (2024), who also reported two peaks in *Phyllostachys pubescens* stands, which varied with the geographic locations of the stands.

Litter nutrients

Litter is the primary carrier of nutrients from plants to soil. This dynamic exchange can achieve and maintain a balance between soil nutrients and the elemental ratios required for plant growth (Hessen et al. 2004). In the present study, nutrient concentrations in the leaf litter exhibited significant variations across different months and seasons. For example, the annual mean concentrations of N and K were higher in *P. roxburghii,* followed by *S. robusta* and *B. tulda*. On the other hand, P concentration was higher in *S. robusta,* followed by *P. roxburghii* and *B. tulda.* The broadleaved plants (short-lived and fast-growing species) have higher growth rates than coniferous plants (long-lived and slow-growing species) and are also rich in N and P and have higher photosynthetic rates (Jing et al. 2017, Zhang et al. 2017, Sun et al. 2021). P concentration in the present study was recorded as higher in broadleaved plantations than in coniferous plantations. Thus, the nutrient traits in the present study differed to some extent between different plantations located in areas with similar climatic conditions. The higher P concentration in pine than in the other plantations can be attributed to enhanced uptake and mineralization in the rhizosphere of conifers (Lin et al. 2022). The greater leaf-litter nutrient status in pine may be due to enriched soil nutrient status, as observed by Spohn and Berg (2023) and Zhang et al. (2021).

In *Pinus roxburghii*, the nutrient concentrations of N and P were highest during the summer, while K levels peaked in winter. In contrast, nutrient concentrations in *Shorea robusta* and *Bambusa tulda* were highest during the winter season. Wu et al. (2005) also reported increased N, P, and K concentrations from May to July and decreased after July, with no significant monthly variation. In the present study, litter N, P, and K concentrations changed irregularly. Different from Yang et al. (2010), who found that N, P, and K exhibit higher concentrations during the growing season, while their levels decrease during autumn and winter, our study observed the lowest N concentration in April and the highest in December. Seasonal variations in nutrient concentrations are significant, exceeding a one-fold difference. P concentration in March is double that in November, and the K concentration in June is 2.7 times higher than in October. The ability to store carbon and the rate of accumulation and supply of N and P that limit plant growth is closely associated. The nutrient limitations in terrestrial ecosystems of different plantations and numerous studies have reported the individual stoichiometries for leaves, litter, and soil (Chen et al. 2016; Song et al. 2016).

Nutrient return

In the present study, the annual pattern of nutrient return was N > K > P in all the plantations. Nutrient return to the forests is controlled by the quantity of litter production and governed by the nutrient contents in the litter (Gonzalez-Rodeıguez et al. 2011). Verma et al. (2021) also reported the turnover rate of nutrients in *P. roxburghii* plantation in the order of Na > K > Ca > Mg > N > P. The amount of N and P on the forest floor and their turnover times are thus markedly longer and controlled by the cumulative nature of microbial biomass (Manral et al. 2023). Das & Mondal (2015) also found a similar order of nutrient return, N > K > P in *S. robusta* and *T. grandis*. Nutrient return through aboveground litterfall represents the most nutrient return to the soil (Bhattarai & Mandal, 2018). The order of nutrient return in the present study is consistent with the results reported for monoculture in *Pinus massoniana* (Lin et al. 2012), *Cinnamomum camphora* and *Aleurites montana* (Lin et al. 2012) plantations in southern China, and different-aged Chinese fir (*Cunninghamia lanceolata*) plantations in south China (Zhou et al. 2015). N, K, and P are the major limiting nutrients returned through litterfall, and they play an essential role in maintaining soil fertility and tree growth in subtropical regions. Lodhiyal et al. (2002) reported nutrient return in the order of N > P > K, and higher P return than K was also noted by Awasthi et al. 2022 in *Coriaria nepalensis*. Thus, it is clear from the earlier works that in temperate and tropical forests, the maximum amount of return of N and K was through litterfall. However, the rate of nutrient return, especially of N, was higher in tropical than in temperate forests, which may be attributed to a higher litterfall rate than in temperate forests. Litterfall and nutrient content significantly vary with the plantation cover, which is the primary route of nutrient return to the soil.

Conclusions

In this study, we investigated the dynamics of litter production and nutrient return across different plantations (*Pinus roxburghii*, *Shorea robusta,* and *Bambusa tulda*) in the humid subtropical region of Uttarakhand, India, to elucidate their roles in nutrient cycling and ecosystem functioning. Litter production was continuous, but the quantity of litter produced varied by season. Maximum litterfall was attained during the dry period (March to June) and minimum in the rainy season (July to September) in the plantations studied at the New Forest estate. Substrate quality seems to be a significant regulatory factor for releasing nutrients through the soil. *B. tulda* exhibited the highest N return, followed by *P. roxburghii* and *S. robusta*. In contrast, P return was greatest in *S. robusta*, followed by *B. tulda* and *P. roxburghii*. K return was highest in *B. tulda*, followed by *S. robusta* and *P. roxburghii*. Overall, the total nutrient return in all plantations was ranked as N > K > P. Leaf litter is one of the significant pathways of nutrient transfer to the soil. The supply of nutrients in an ecosystem is highly influenced by litter quality, its input, and the decay rate. The present study concluded that these plantations have a vital nutrient conservation mechanism, as evident from high litter production and nutrients returned to the soil. Our results demonstrated significant differences in litterfall quantities and nutrient return rates among the different plantation types, supporting our first hypothesis that these differences are due to their distinct physiological and ecological characteristics. The data also revealed significant monthly and seasonal variations in nutrient concentrations, with each plantation type exhibiting distinct patterns, thereby confirming our second hypothesis. The present study successfully met its aims and objectives by providing a detailed evaluation of nutrient dynamics in the specified plantation types. The findings highlight the importance of species-specific influences on nutrient cycling and biogeochemical processes in humid subtropical ecosystems.

Conflict of interest

The authors declare no financial or personal interests could influence the work presented in this paper.

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