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RESEARCH ARTICLE

Soil carbon dynamics driven by bamboo litter decomposition in the Western Ghats: Implications for ecosystem carbon cycling

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Abstract

Bamboo ecosystems, known for their rapid biomass production and high carbon sequestration potential, are key contributors to ecological functioning. This study delves into the intricate carbon dynamics within five distinct bamboo species–*Bambusa balcooa*, *Dendrocalamus strictus*, *D. giganteus*, *D. brandisii* and *Guadua angustifolia*. This research was conducted in the Kattippara village of the Thamarasseri block within the biodiversity-rich Western Ghats of Kozhikode district, Kerala and it investigates variations in three key ecological processes: soil organic carbon (SOC) storage, litterfall-driven organic matter flux and the decomposition and reintegration of litter into the soil. Our findings reveal significant interspecies differences in annual litterfall–a crucial pathway for carbon input into the soil–ranging from 4.575 to 6.828 Mg ha^{-1} yr^{-1}, with *D. strictus* demonstrating the highest litter productivity. Furthermore, the rate at which this organic matter is broken down and nutrients are released back into the ecosystem, as indicated by litter decomposition constants (k ranging from 0.2173 to 0.2858 $month^{-1}$), also varied significantly across the studied species. The organic carbon content of the upper soil layer (0-15 cm) exhibited variations, suggesting a strong link to both the quantity and quality of litter inputs and their decomposition dynamics. This comparative ecological assessment provides critical insights into the functional diversity of different bamboo species and their respective contributions to carbon cycling within the landscape. The study underscores the importance of informed species selection for afforestation projects and carbon sequestration strategies aimed at maximizing ecosystem benefits.

Keywords: bamboo; carbon sequestration; litter decomposition; litter fall; soil organic carbon

Introduction

Bamboo holds immense economic and ecological importance as a fast-growing, versatile resource with significant potential for soil health improvement and carbon sequestration. But there is a notable research gap concerning the specific mechanism of carbon dynamics within different bamboo species. Many studies have explored the carbon storage capabilities of various forest ecosystems. Understanding species-specific differences is crucial for developing effective, sustainable management strategies for bamboo afforestation policies. Despite the growing popularity and ecological significance of bamboo in the Western Ghats region, only a few studies have investigated its specific role in local ecosystems.

Bamboo, a fast-growing member of the Poaceae family, holds significant ecological and economic importance, particularly in tropical and subtropical regions (1). Bamboo protects steep slopes, soils and waterways and provides carbon sequestration. Its rapid growth and substantial biomass production significantly contribute to carbon sequestration, positioning it as a potential asset in climate change mitigation (2). Therefore, comprehending the carbon cycling dynamics within bamboo ecosystems, notably through litter fall and decomposition pathways, is essential for evaluating their impact on SOC storage and overall ecosystem functionality.

Annual litter fall, the deposition of dead plant matter onto the forest floor, constitutes a primary mechanism for carbon and nutrient translocation from vegetation to the soil (3). Litter quality and biochemical makeup, both of which can differ substantially among plant species, directly determine the rate of decomposition and the resulting build-up of SOC (4). The decomposition of litter, facilitated by soil microorganisms and fauna, is a critical process for nutrient recycling and plays a significant role in maintaining soil fertility and regulating carbon cycling (5).

Despite the acknowledged potential of bamboo ecosystems for carbon sequestration, comparative research on litter fall, decomposition dynamics and SOC across different bamboo species remains somewhat scarce. Inter-species variations in morphological and physiological attributes can result in differing litter characteristics (e.g., carbon to nitrogen ratio, lignin concentration), which, in turn, can influence decomposition rates and SOC accumulation (6). A review of 184 studies encompassing 70 bamboo species indicated that SOC levels range from 70 MgC ha^{-1} to 200 MgC ha^{-1} (7). They emphatically opined that bamboo should be granted considerably greater recognition in national and international policy frameworks and management strategies. This is particularly important as bamboo serves as a significant carbon sink, making it a valuable component in climate change mitigation. Beyond its remarkable capacity for carbon sequestration, bamboo possesses a multifaceted ability to provide a range of essential ecosystem services vital for human civilization. Its extensive root system enhances soil fertility by binding particles and adding organic matter, while also serving as a natural barrier to erosion on degraded or sloping lands.

Furthermore, bamboo offers direct benefits to human well-being by providing a sustainable source of food through its nutritious shoots and serving as a versatile, rapidly renewable raw material for construction and various other products. Integrating bamboo more prominently into policy and management would therefore unlock its full potential for ecological restoration, climate resilience and socio-economic development. From an ecological standpoint, this study investigates and compares the SOC storage, the annual flux of organic matter through litter fall and the rates of nutrient and carbon release through litter decomposition among five ecologically diverse bamboo species: *B. balcooa*, *D. strictus*, *D. giganteus*, *D. brandisii* and *G. angustifolia*. Recognizing that these species exhibit a spectrum of growth patterns and ecological adaptations, this research aims to elucidate the variations in fundamental carbon cycling processes. By quantifying these key ecological parameters, the study seeks to enhance our understanding of carbon dynamics within differing bamboo ecosystems, ultimately providing ecologically informed insights for management strategies focused on optimizing carbon sequestration and promoting soil health.

Materials and Methods

Study site and species selection

The study was conducted in Kattippara village of Kozhikkode district, Kerala, located at N 11°29'7.11" N latitude and 75°54'44.20" E longitude. The study area experiences a tropical monsoon climate, characterized by high temperatures and humidity throughout the year (Fig. 1). For the study, the selected species of bamboo, namely, *D. brandisii* (Munro) Kurz., *D. giganteus* Munro, *B. balcooa* Roxb., *G. angustifolia* Kunth. and *D. strictus* (Roxb.) Nees. Species identification has been made using the herbarium data provided by the Kew Gardens website https://powo.science.kew.org (8). Representative clumps of comparable age (seven years) and management history were selected for each species.

Litter fall measurement

Litter fall data were collected over a one-year period, from September 2023 to August 2024, for the five bamboo species under investigation. To capture falling organic matter, one-square-meter (1 × 1 m) litter boxes were strategically positioned at the four cardinal directions (North, South, East and West) within each bamboo stand. These traps were emptied at monthly intervals. The collected litter from each trap was then oven-dried at a consistent temperature of 60 °C until a stable weight was achieved. The average dry weight of litter collected per square meter was then scaled up to estimate the annual litter fall production, expressed in Megagrams per hectare per year (Mg ha^{-1} yr^{-1}).

Litter decomposition measurement

Litter decomposition rates were assessed using the litter bag technique, with minor adjustments (9). Freshly senesced leaves from each of the five bamboo species were gathered during their peak litter fall period. These fresh leaf samples were then placed into nylon mesh bags, each measuring 20 cm × 20 cm with a 2 mm mesh opening. The filled litter bags were randomly distributed on the forest floor within the respective bamboo stands, ensuring direct contact with the soil surface. At monthly intervals, from May 2023 to April 2024, a subset of litter bags was retrieved to measure the wet weight of the remaining litter. Following this measurement, the same litter bags were returned to their original locations in the field. The decomposition rate constant (*k*) was calculated using the negative exponential decay model:

$$Wt = W0 \times e\,(-kt) \quad \text{(Eqn.1)}$$

where: Wt = mass remaining at time t, W0 = initial mass, k = decomposition rate constant (per year, yr^{-1}) t = time (in years).

Soil organic carbon analysis

Soil samples were collected from each study plot at three distinct depth intervals: 0-5 cm, 5-10 cm and 10-15 cm, using a soil auger. At each depth within each plot, three replicate samples were obtained and then combined to form a single composite sample representing that depth. These soil samples were subsequently air-dried and sieved through a 2 mm mesh to remove any coarse fragments. The SOC content of the processed samples was then determined using the Walkley-Black wet oxidation method (10). The resulting SOC content was expressed as a percentage of the soil mass.

Statistical analysis

Statistical analyses were performed by writing Python code within the Google Colaboratory environment (11). One-way analysis of variance (ANOVA) was employed to compare the means of annual litter fall, decomposition rate constants (*k*) and SOC content across the five bamboo species. When overall significance was detected, Tukey's honestly significant difference (HSD) *post-hoc* test was employed to determine specific pairwise differences among species means, using a significance level of $p < 0.05$. Additionally, correlation analysis was conducted to evaluate the statistical relationships between litter fall amounts, decomposition rates and soil organic carbon content.

Results

Annual litter fall

Annual litter fall exhibited significant variation across the five studied bamboo species, revealing distinct species-specific patterns while displaying only modest seasonal fluctuations. Based on the total annual litter production, the species can be categorized into high, medium and low litter fall classes (Fig. 2). *D. strictus* demonstrated the highest annual litter fall (6.828 ± 0.22 Mg ha^{-1} yr^{-1}), closely followed by *B. balcooa* (6.750 ± 0.20 Mg ha^{-1} yr^{-1}). In contrast, *G. angustifolia* recorded the lowest annual litter fall (4.174 ± 0.24 Mg ha^{-1} yr^{-1}). A slight peak in litter fall was observed around April and May for most species. ANOVA on litter fall data reveals significant differences (Table 1). Despite the numerical variations in the litter fall from month to month, the statistical analysis indicates that there are no statistically significant differences in the average litter fall when comparing any specific month to another. This means that at the chosen significance level ($\alpha = 0.05$), the monthly fluctuations in litter fall are not large enough to be considered statistically different.

Litter decomposition rates

ANOVA reveals statistically significant differences in the average mass of leaf litter remains among the different species (Table 2). But not all species decompose at the same time. There are significant differences in the average mass of leaf litter remains across the

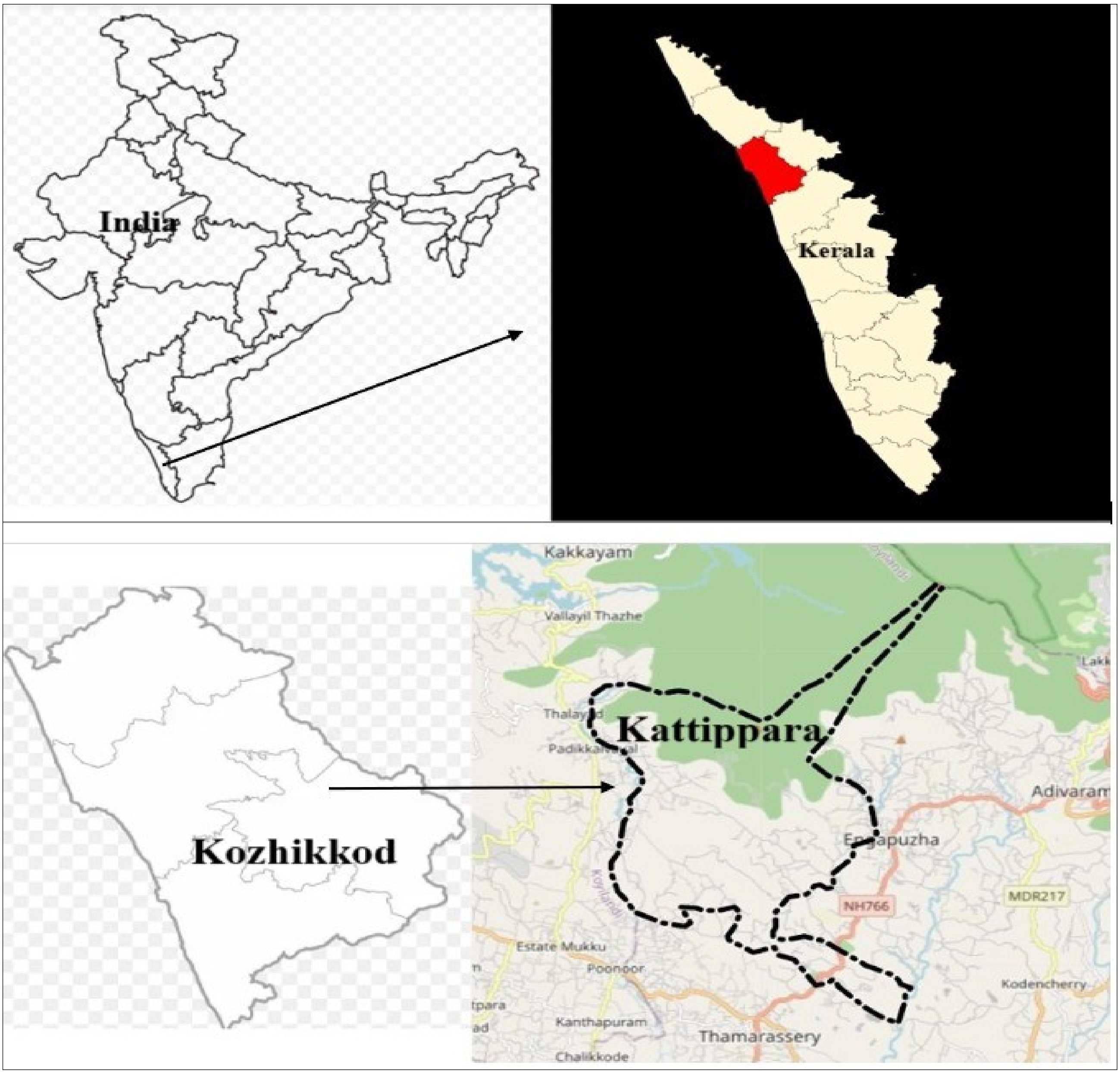

Fig. 1. Study site.

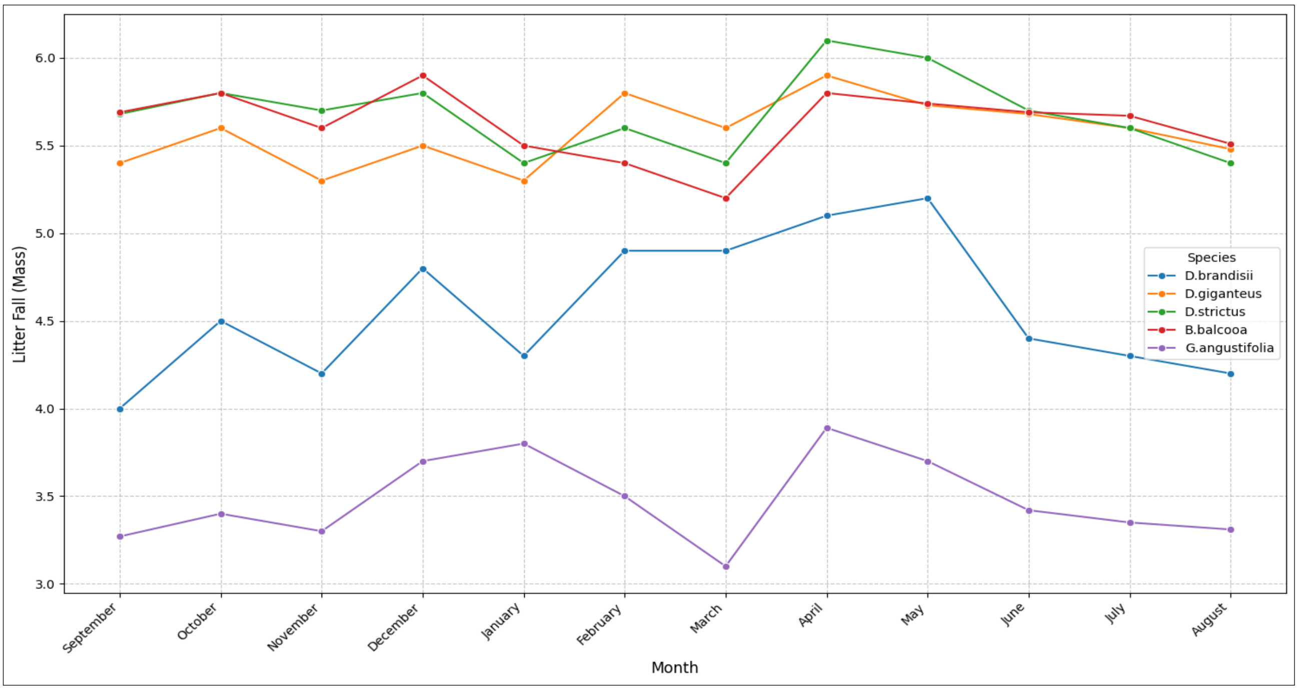

Fig. 2. Litter fall pattern showing monthly variations for the five bamboo species.

different months. The decomposition of litter across all five bamboo species followed a broadly similar temporal trend, as illustrated by the percentage of remaining litter mass each month since May (Fig. 3). The most rapid mass loss was observed between September and December. Notably, *G. angustifolia* consistently exhibited the lowest remaining litter mass throughout the decomposition period. The other four species displayed highly similar decomposition patterns, particularly during the later months of the study.

Soil organic carbon content

The mean SOC content in the topsoil layer (0-15 cm) varied significantly among the five bamboo species (F = 5.33, $p < 0.012$). Specifically, *D. brandisii* exhibited the highest mean SOC content (3.47 %), while *G. angustifolia* recorded the lowest (3.23 %). A consistent trend of decreasing SOC content with increasing soil depth was observed across all bamboo stands (Table 3). The top 5 cm consistently shows higher SOC content. The difference between the highest (*D. brandisii*) and lowest (*G. angustifolia*) mean SOC is statistically insignificant.

Correlation analysis

Correlation analysis indicated the presence of both positive and negative relationships among the measured variables. As depicted in the correlation matrix, the strongest relationship was a moderate negative correlation observed between litter fall and the rate of decomposition (Fig. 4). The percentage of SOC showed a moderate positive correlation with the rate of litter decomposition, while its correlation with litterfall amount was weakly positive. Regression analysis revealed that SOC content in both the 0-5 cm and 5-10 cm soil layers had a significant and positive effect on the overall mean SOC. In contrast, the SOC content in the 10-15 cm soil layer did not exhibit a statistically significant effect on the mean SOC.

Discussion

The significant variations in annual litter fall observed across the five bamboo species likely stem from inherent differences in their biomass production capacities, growth architectures and phenological characteristics, such as the duration and intensity of leaf shedding. A key observation was the overall similarity in decomposition rates and the final percentage of remaining mass across species, despite differences in initial litter mass. This suggests that environmental factors may exert a primary influence on the decomposition process in this study site.

In comparison, a separate litter bag experiment reported a 50 % decomposition time of 235 days (12). In addition, litter decomposition is regulated by the combined effects of litter mixing and microbial community composition, thereby highlighting the role of plant community structure in driving soil carbon and nutrient dynamics (13). A model proposed microbial enzyme production traits as significant controls on litter decomposition rates (14). The most prominent relationship is the strong negative correlation between decomposition rate (*k*) and SOC (Fig. 4). This highlights the critical role of litter decomposition speed in influencing the amount of SOC stored in the soil. Slower decomposition appears to be a key factor in higher soil organic carbon accumulation. Further research is warranted to explore these complex interactions in the context of these specific bamboo ecosystems.

The higher litter fall recorded for *D. strictus* indicates a potentially greater contribution of carbon to the soil compared to species exhibiting lower litter production. These findings align with previous research highlighting species-specific variations in litter fall within forest ecosystems (15). Another study reported that 50 % of litterfall decomposed within 2.1 years, while 95 % took 9.1 years (16). It is well-established that litter quality, including its chemical composition, is a primary factor influencing the rate of decomposition (17). Despite variations in their initial biomass, all five bamboo species exhibited similar rates of decomposition and reached comparable final decomposition percentages (Table 4). This suggests that environmental conditions at the study site may exert a stronger influence on the decomposition process than inherent species-specific litter characteristics. While factors such as lignin and cellulose content, carbon to nitrogen (C: N) ratio and the presence of secondary compounds are known to affect the activity of decomposer microorganisms, the overall decomposition patterns in this study were remarkably consistent across species (5).

Over the 12 months observation period (May to April), all species experienced substantial decomposition, with only approximately 4 % of their initial mass remaining at the end. Total decomposition ranged from 95 % to 97 %, with *B. balcooa* showing a slightly higher total decomposition (96.3 %). It's worth noting that temperature has been identified as a key driver of forest litterfall (18). A global relationship has been identified between litter decomposability and species' ecological strategies, linking whole-plant carbon allocation to biogeochemical cycling across ecosystems (6). However, the complexity of organic matter decomposition relationships highlights the need for caution when drawing definitive mechanistic conclusions from field studies (19).

Table 1. Analysis of variance (litter fall)

	Sum of squares	Degrees of freedom (df)	F-statistic	probability (> F)
Species	44.24	4	275.82	1.5 e^{-30}
Months	1.97	11	4.47	1.2 e^{-04}
Residual	1.76	44		

Table 2. Analysis of variance (decomposition of litter)

	Sum of squares	Degrees of freedom (df)	F-statistic	probability (> F)
Species	0.1005	4	12.1017	1.02 e^{-30}
Months	2.0044	11	87.7754	3.40 e^{-04}
Residual	0.0913	44		

Table 3. Litterfall, k-value and soil organic carbon

Species name	Litterfall (mg ha^{-1} yr^{-1}).	Litter decomposition constant (k-value)	Soil organic carbon (%)
Dendrocalamus brandisii	5.480	0.3188	3.47
Dendrocalamus giganteus	6.689	0.3151	3.40
Dendrocalamus strictus	6.818	0.3236	3.25
Bambusa balcooa	6.750	0.3397	3.34
Guadua angustifolia	4.174	0.3410	3.23
Mean	5.982	0.33	3.34
S.D.	1.152	0.01	0.10

Table 4. Decomposition changes

Species Name	Weight loss (kg)	Decomposition (%)
Dendrocalamus brandisii	0.39	96.1
Dendrocalamus giganteus	0.52	95.9
Bambusa balcooa	0.55	96.3
Guadua angustifolia	0.31	96.0
Dendrocalamus strictus	0.54	96.0

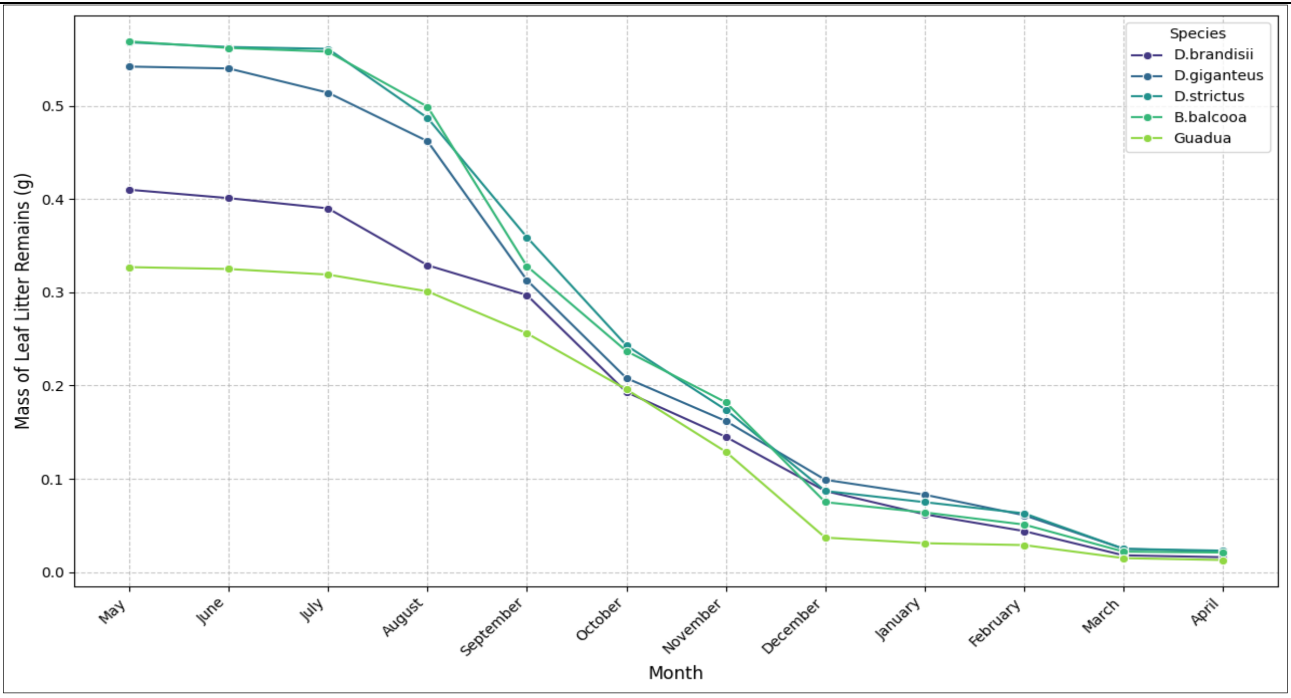

Fig. 3. Monthly litter mass remaining.

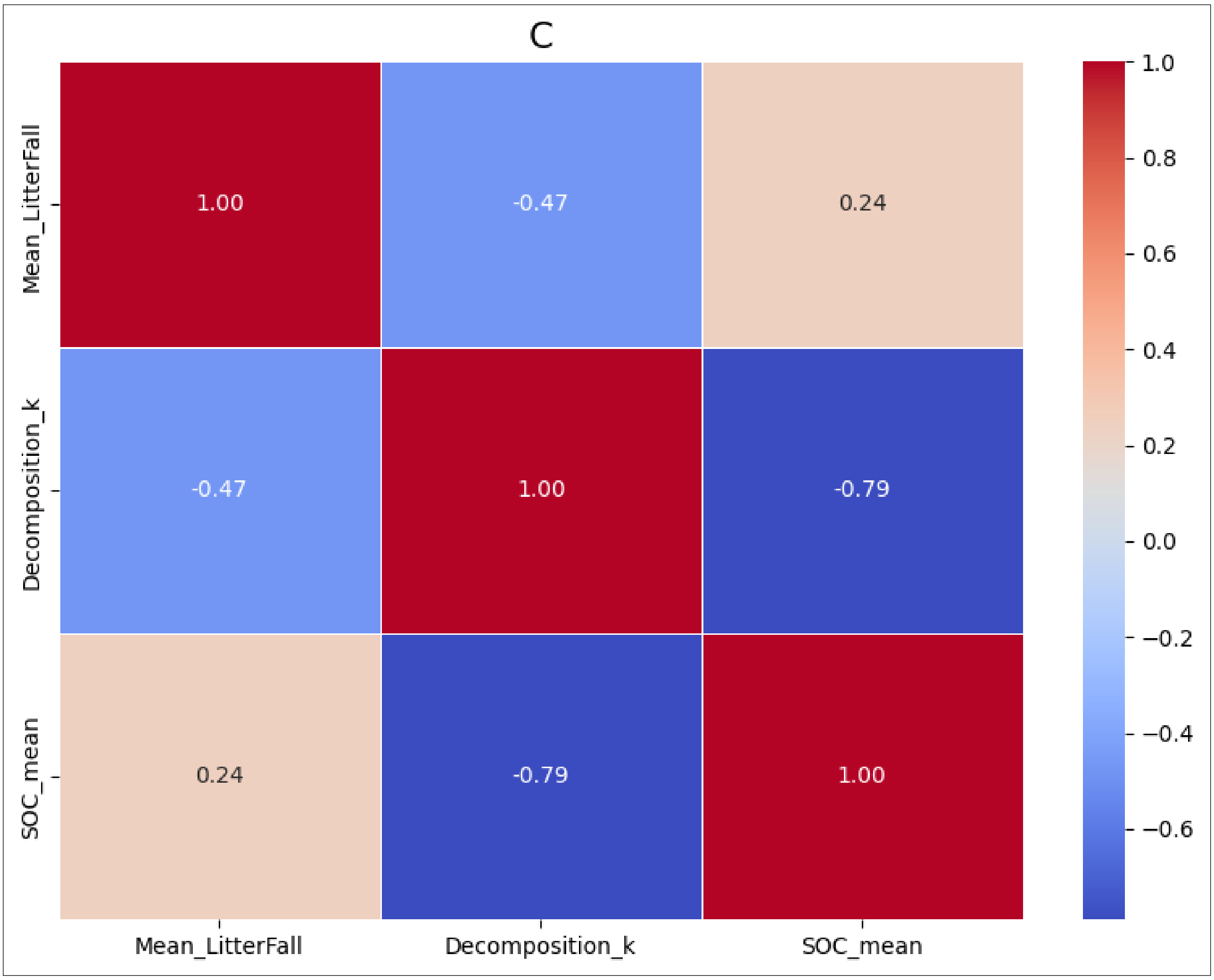

Fig. 4. Correlation matrix.

The subtle differences observed in monthly decomposition rates suggest that seasonal environmental fluctuations or minor variations in species-specific litter properties might slightly modulate the speed of decomposition.

Litter fall itself has a weaker, slightly positive relationship with SOC and a moderate inverse relationship with decomposition rate. This suggests that while litter input is important, the rate at which it decomposes is a more influential factor for SOC dynamics in this ecosystem. Nevertheless, these findings generally support the well-established principle that litter quality plays a significant role in decomposition dynamics (4). The design of litter decomposition studies is recommended to include substantial within-site replication and biome-scale perspectives to better capture the complexity of these processes (20). They questioned the assumption that climate is the predominant regulator of decomposition rates and proposed a framework for a new generation of studies focusing on factoring local-scale variations. Under contemporary paradigms, climate and litter quality are considered the dominant factors regulating the rate at which organic matter decomposes. The observed variations in SOC content among the bamboo species likely result from the integrated effects of litter fall input and the rates of its subsequent decomposition. The higher SOC content under *D. brandisii* could be attributed to a combination of moderate litter fall and relatively slower decomposition, leading to organic matter accumulation or a more complex interplay of factors influencing both carbon input and turnover.

Interestingly, while *D. strictus* exhibited the highest litter fall, its average litter decomposition rate was among the lowest and it had a lower SOC percentage. This suggests that despite a high input of organic matter, its slower breakdown might limit its contribution to stable soil carbon. Conversely, *D. brandisii*, with moderate litter fall and the highest average litter decomposition, also had the highest SOC percentage, indicating efficient conversion of its litter to SOC. *G. angustifolia*, with the lowest litter fall and the lowest SOC percentage, likely contributes less overall organic matter to the soil. The correlation analysis hints at a potential link between litter fall quantity and SOC accumulation, but this relationship appears complex and is likely influenced by other factors such as soil type, climate and the composition of the soil microbial community. Consistent with our findings of higher SOC in topsoil, similar studies reported a decrease in SOC stock with increasing soil depth, with the highest concentration in the 0-20 cm layer (21, 22).

Variations in climate, soil sampling depth and methodologies contribute to the range of SOC values reported across different studies. Considerable variability has been reported in global SOC estimates (22). Despite the large carbon reservoir held in SOC, a clear consensus on the size, distribution and emissions from soil carbon due to land-use change remains elusive. However, a large-scale indicated that topsoil experiences the greatest proportion of SOC losses, particularly in high-latitude, carbon-rich systems, a trend contrary to our finding of greater SOC accumulation in the topsoil (24). The differences in SOC content among the bamboo species may indeed be linked to the varying amounts of litter they contribute to the soil (25). The findings of this study open significant implications for managing bamboo ecosystems for carbon sequestration and enhancing soil health. Selecting bamboo species with high litter fall and appropriate decomposition rates could optimize carbon input and long-term storage in the soil. Long-term studies focusing on the sustainable development of bamboo ecosystems are recommended (26). Further research is necessary to elucidate the specific litter quality parameters that govern decomposition rates and to understand the long-term impacts of different bamboo species on SOC dynamics under diverse environmental conditions.

Conclusion

This study demonstrates significant ecological differences among five bamboo species regarding soil carbon, litter production and decomposition, highlighting the complex interactions between litterfall, decomposition and SOC accumulation in bamboo ecosystems. While *D. strictus* exhibited the highest litter production, its slower decomposition appeared to limit its contribution to stable SOC. Conversely, *D. brandisii* demonstrated an optimal balance, characterized by moderate litterfall and efficient decomposition, which led to the highest SOC. This highlights that both the quantity and quality of litter, alongside environmental factors, are crucial for effective carbon sequestration. Strategic selection of bamboo species based on these dynamics can significantly enhance soil health and carbon storage in these valuable ecosystems. Further research into the mechanisms driving these variations will improve our understanding of carbon cycling in bamboo ecosystems. Thus, natural farming can be regarded as an innovative and sustainable agricultural strategy that resonates with global priorities for regenerative farming, while simultaneously improving soil health, yield performance and environmental sustainability.

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Authors' contributions

SKP contributed to conceptualisation, methodology, data collection, analysis, interpretation of results and writing and editing of the manuscript. SS provided guidance, critical feedback and oversight throughout the research process. All authors read and approved the final manuscript.

Compliance with ethical standards

As a researcher, I commit to conducting my research in accordance with ethical guidelines that prioritize participant consent, confidentiality and data integrity. I will ensure that all findings are reported honestly and without bias. This work aims to contribute to the body of knowledge while maintaining the highest ethical standards.

Conflict of interest: The Authors do not have any conflicts of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process : During the preparation of this work, the authors used “Grammarly” to improve the writing style, grammar and spelling. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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