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RESEARCH PAPER

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Biomass and carbon stocks of fine litterfall and coarse woody debris in riparian and non-riparian tropical forests of Carmen, Bohol, Philippines

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ABSTRACT

Forests play a vital role in terrestrial ecosystems by regulating nutrient cycling, promoting biodiversity, and storing carbon. Fine litterfall and coarse woody debris (CWD) are key contributors to forest carbon pools, yet their relative roles in tropical forests are not well understood. This study quantified the biomass and carbon stocks of fine litterfall and CWD in riparian and non-riparian forests in Carmen, Bohol, Philippines, and assessed their contributions to overall forest carbon sequestration. One-hectare permanent plots were established in each forest type, with subplots and quadrats for collecting litterfall and measuring CWD. Fine litterfall was oven-dried to determine biomass and carbon content, while CWD was measured for diameter, length, decay class, and species-specific wood density. Carbon stocks were calculated using allometric and decay-based models, and differences between forest types were analyzed using two-sample t-tests. Results showed that non-riparian forests had higher fine litterfall biomass (21.58 Mg ha^{-1}) and carbon (10.79 Mg C ha^{-1}) than riparian forests (16.03 Mg ha^{-1}; 8.02 Mg C ha^{-1}). Similarly, CWD biomass and carbon were greater in non-riparian forests (65.58 Mg ha^{-1}; 29.51 Mg C ha^{-1}) than in riparian forests (38.24 Mg ha^{-1}; 17.21 Mg C ha^{-1}), reflecting differences in tree composition, stand age, and decomposition rates. Fine litterfall provides rapid nutrient inputs, whereas CWD serves as a long-term carbon reservoir and structural habitat. Incorporating both components into carbon assessments enhances forest management, conservation planning, and climate change mitigation. The study underscores the importance of conserving both riparian and non-riparian forests to optimize carbon sequestration and maintain ecosystem functions.

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INTRODUCTION

Forests are essential components of terrestrial ecosystems, regulating nutrient cycling, biodiversity, and carbon sequestration. Two key contributors to forest ecosystem function are fine litterfall and coarse woody debris (CWD), both of which influence soil fertility, forest productivity, and long-term carbon storage. Fine litterfall, composed of leaves, flowers, fruits, and small twigs, acts as a conduit between the canopy and soil, delivering organic matter and essential nutrients that support microbial activity and enhance soil organic carbon (Krishna and Mohan, 2017; Pitman, 2013). The quantity and quality of litterfall depend on the diversity of tree species, forest age, and stand structure, which in turn influence decomposition rates and nutrient availability (Huang *et al.*, 2017; Giweta, 2020). Despite its recognized ecological importance, studies quantifying fine litterfall production and decomposition in tropical forests remain limited, particularly in the context of long-term carbon storage and sustainable forest management.

Complementing the role of fine litterfall, coarse woody debris (CWD) is another critical component of forest ecosystems. CWD, including fallen logs, standing dead trees, and large branches, supports nutrient cycling, provides structural habitat, contributes to carbon sequestration, and facilitates the regeneration of plant and animal communities (Shvidenko *et al.*, 2024; Manning *et al.*, 2013; Khan *et al.*, 2021). As woody debris decomposes, it gradually releases nutrients, such as nitrogen, phosphorus, and potassium, into the soil, thereby enhancing tree growth and overall forest resilience (Spohn, 2016; Small, 2024). Furthermore, CWD serves as a long-term carbon reservoir, with decay rates influenced by species, decomposition stage, and environmental conditions, thereby modulating carbon fluxes over time (Adamczyk *et al.*, 2020; Harmon *et al.*, 2020). Nevertheless, integrated studies that simultaneously examine both woody and non-woody litter dynamics in tropical forests are scarce, particularly in relation to forest succession, biodiversity, and carbon stock estimation (Wang *et al.*, 2021; Yuan *et al.*, 2017).

Together, the contributions of fine litterfall and CWD highlight the importance of forests as major carbon pools. Forests sequester atmospheric carbon dioxide, storing carbon across living and dead trees, understory vegetation, litter layers, and soils, with each pool contributing differently to overall carbon dynamics (Russo *et al.*, 2023; Noormets *et al.*, 2021). In the Philippines, where forest types vary widely in terms of species composition, management history, and stand age, accurate carbon stock estimation is particularly crucial (Lasco and Pulhin, 2009). Existing studies indicate significant carbon losses following logging, land-use change, or forest degradation, emphasizing the need to quantify the contributions of both fine litterfall and CWD to support sustainable forest management and climate change mitigation (Durkay *et al.*, 2016; Haya *et al.*, 2023; Hurmekoski *et al.*, 2022; Lefebvre *et al.*, 2021).

Despite the growing recognition of their ecological and climatic importance, notable knowledge gaps remain. Few studies have quantified biomass and carbon stocks of fine litterfall and CWD across different forest cover types, including riparian and non-riparian forests. Additionally, the relationship between these litter components and overall ecosystem carbon storage is poorly understood, limiting the development of evidence-based strategies for carbon sequestration and biodiversity conservation. To address these gaps, this study focuses on Carmen, Bohol, a representative lowland tropical forest in the central Philippines featuring both riparian and non-riparian patches, diverse tree species composition, and varying degrees of human disturbance.

The presence of riparian corridors presents a unique opportunity to examine spatial differences in the contributions of litter and woody debris to carbon storage, offering insights applicable to local forest management and conservation planning.

Accordingly, this study aims to estimate the biomass and carbon stocks of fine litterfall and coarse woody debris in riparian and non-riparian forests in Carmen, Bohol, and to examine the relationship between biomass and carbon stock in these two litter components. By integrating these objectives, the study aims to provide a baseline for forest carbon accounting, inform sustainable management strategies, and support climate change mitigation efforts in tropical forest ecosystems.

MATERIALS AND METHODS

Study site

This study was conducted in two distinct forest types: a riparian forest in Barangay Nueva Vida Norte (9.794293, 124.182702) and a non-riparian forest in Barangay Buenos Aires (9.976425, 124.17972) (Fig. 1). The riparian forest marked the boundary line between the two mentioned barangays. The area was composed of various vegetation, including trees, shrubs, vines, and grass, which made it more productive. However, the non-riparian forest comprises big mahogany trees, shrubs, vines, minimal grass, and other vegetation. Moreover, the riparian forest, with its higher moisture levels and diverse vegetation, was expected to influence the decomposition rates and carbon sequestration potential of CWD and fine litterfall, whereas the non-riparian forest offers a contrasting environment for comparison. By assessing the carbon stored in these two components, the study aims to provide insights into the role of riparian zones in carbon fluxes and deepen our understanding of tropical forest carbon dynamics. The findings will inform better forest management practices, contributing to climate change mitigation efforts through more effective carbon sequestration strategies.

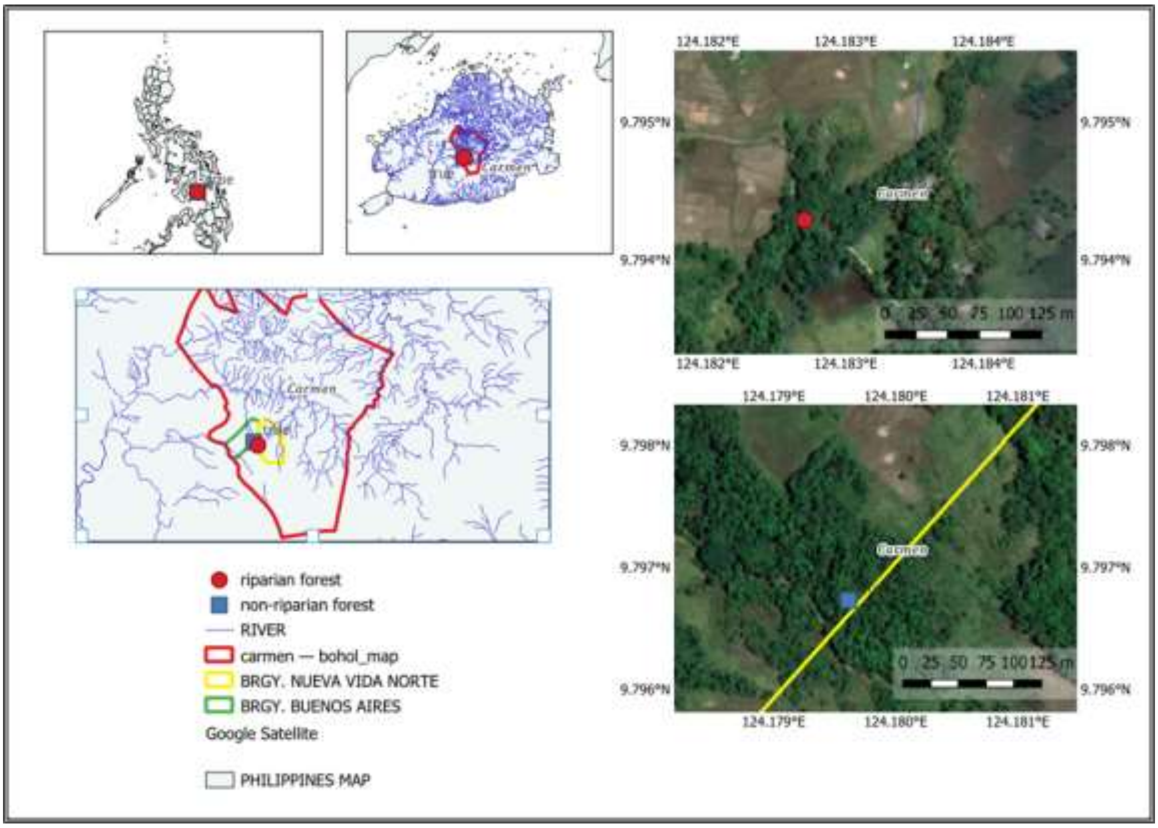

Fig. 1. Location map of the study

Design

The study was conducted within a one-hectare permanent forest plot. To ensure representative sampling while minimizing edge effects, a 60 m × 60 m subplot was established at the center of the plot, from which eight 20 m × 20 m quadrats were randomly selected for detailed measurements (Fig. 2). Quadrats along the plot boundary were excluded to prevent external litter and debris from influencing results. Within each quadrat, a 10 m × 10 m sub-subplot was delineated for fine litterfall collection, with three 0.5 m × 0.5 m sampling points established to ensure spatial coverage. All coarse woody debris (CWD) within the quadrats was measured for diameter and length, linking the study design directly to both fine and coarse litter assessment.

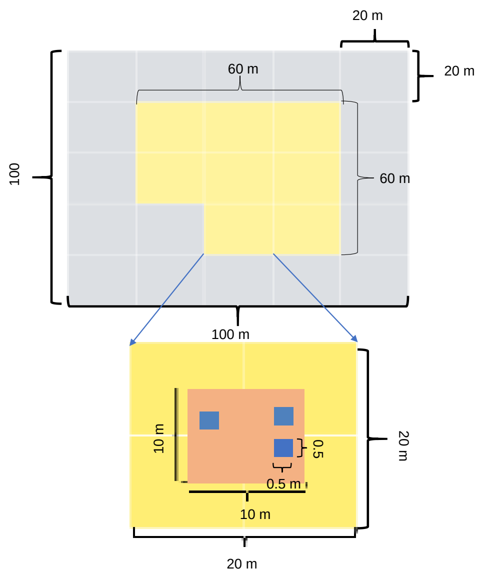

Fig. 2. Sampling design of the study

Fine litterfall collection

Building upon the subplot framework described above, five of the eight 20 m × 20 m quadrats were randomly selected for fine litterfall collection. In the center of each quadrat, a 10 m × 10 m sub-subplot was established for litter trap installation. Within each sub-subplot, three 0.5 m × 0.5 m sampling points were randomly positioned to capture spatial variability in litterfall. Fine litterfall at these points was collected by hand, and the total fresh weight was measured. Samples were transported to the Bohol Island State University (BISU) Soil Laboratory, where a 200-g subsample from each composite sample was oven-dried at 65°C for 72 hours or until a constant weight was achieved. After cooling for at least five minutes, the dry weight was recorded for biomass calculations.

Coarse woody debris collection

In addition to fine litterfall, coarse woody debris (CWD) within the same eight 20 × 20 m quadrats was assessed. Only dead wood or fallen trunks with a minimum diameter of 10 cm at the widest part were measured for classification and identification (Yan *et al.*, 2006). For logs partially outside the plot boundary, only the portion within the plot was included. Decay was identified according to the classification of Harmon *et al.* (2013). The five decay classes were defined as:

Class 1: Sound, freshly fallen, intact logs with no rot, no conks present indicating a lack of decay, the original color of wood, no invading roots, fine twigs attached with tight bark;

Class 2: Sound log sapwood is partly soft but can't be pulled apart by hand, the original color of wood, no invading roots, many fine twigs are gone, and remaining fine twigs have to peel bark;

Class 3: Heartwood is still sound with a piece supporting its own weight; sapwood can be pulled apart by hand or is missing; wood color is the reddish-brown or original color; roots may be invading sapwood; only branch stubs are remaining, which can't be pulled out of log;

Class 4: Heartwood is rotten, with piece unable to support its own weight, rotten portions of the piece are soft and/or blocky in appearance, a metal pin can be pushed into heartwood, wood color is reddish or light brown, invading roots may be found throughout the log, branch stubs can be pulled out; and

Class 5: There is no remaining structural integrity to the piece with a lack of shape as rot spreads out across the ground; the rotten texture is soft and can become dry powder when dry, the wood color is red-brown to dark brown, invading roots are present throughout, branch stubs and pitch pockets have usually rotten down. In calculating the biomass, the dead tree species wood density value is based on the decay class category for 1=0.56 g cm^{-3}, 2=0.49 g cm^{-3}, 3=0.37 g cm^{-3}, 4=0.28 g cm^{-3}, and 5=0.15 g cm^{-3}, (Shorohova *et al.*, 2021).

Fine litterfall

Following sample collection, biomass and carbon stock were calculated for both fine litterfall and coarse woody debris. For fine litterfall, biomass was estimated using the formula of Kohler *et al.* (2008):

Biomass fine litter fall= Total fresh weight × {(Subsample dry weight)/(Subsample fresh weight)}

Carbon stock fine litter fall= Biomass fine litter fall × % OC

Coarse woody debris

The coarse woody debris was calculated with an equation based on cylindrical volume.

Biomass coarse woody debris = $\pi d^2 ls/ 400\ m^{-2}$

Where: biomass (Mg ha^{-1}), d = tree diameter (cm), l = length (m), s=wood density (g cm-3); for dead tree species, a wood density value is based on the five-decay classification was used (Shorohova *et al.*, 2021).

Carbon stock was estimated as follows (e.g., Chave *et al.*, 2014).

Carbon stock cwd = Biomass CWD × 0.45

Statistical treatment

To assess differences in carbon stock between riparian and non-riparian forests, statistical analyses were conducted. A two-sample t-test, assuming equal variances, is used to compare site means at a significance level of 0.05. The analysis generated group means, variances, t-statistics, degrees of freedom, and p-values. Based on the p-value, the null hypothesis was either rejected or retained to determine whether there were significant differences in carbon storage between the two forest types. All statistical procedures were performed using the Data Analysis Toolpak in Microsoft Excel 2023.

RESULTS AND DISCUSSION

Composition and functional roles of fine litterfall

The composition of fine litterfall revealed that leaves dominated both riparian and non-riparian forests, comprising 68.61% and 78.37%, respectively (Table 1). Twigs were the second most abundant component, accounting for 31.39% in riparian areas and 21.30% in non-riparian areas, while fruits and seeds appeared only minimally in non-riparian forests (0.33%). The absence of flowers and inflorescence in both forest types suggests either limited reproductive litter during the sampling period or rapid decomposition of these materials. Taken together, these proportions indicate functional differences between forest types: riparian forests experience greater structural litter inputs from twigs, whereas non-riparian forests are characterized by more foliar input.

Building on this observation, the higher proportion of twigs in riparian forests may reflect hydrological and physical disturbances that promote branch shedding. In contrast, the greater leaf fraction in non-riparian forests indicates a more stable canopy and efficient litter production.

These compositional differences have direct implications for nutrient cycling and soil fertility, as leaves are major contributors to nutrient input, providing essential elements such as nitrogen, phosphorus, and potassium that are vital for plant growth (Sánchez *et al.*, 2008; Sloboda *et al.*, 2017).

From a nutrient-cycling perspective, leaves decompose more rapidly than twigs, facilitating the faster release and recycling of nutrients that support both primary and secondary productivity in forest ecosystems (Sánchez *et al.*, 2008). The rate of leaf decomposition and nutrient release is further influenced by environmental conditions, with higher rates typically observed during warmer and wetter periods (Sloboda *et al.*, 2017). Moreover, high plant biodiversity accelerates decomposition, enhancing nutrient cycling and overall soil fertility (Furey *et al.*, 2021; McLaren, 2014).

In contrast to the rapid nutrient turnover of leaves, twigs play a more enduring role in the carbon cycle. Their slower decomposition, due to higher lignin content and greater structural complexity, allows them to contribute to long-term carbon storage in soils (Kammer and Hagedorn, 2011; Hobbie, 2015). Consequently, carbon derived from twig litter is less prone to leaching or mineralization, leading to its stabilization within the soil organic matter pool (Kammer and Hagedorn, 2011). This stability highlights the crucial role of woody debris in sustaining long-term soil organic carbon, particularly in forest ecosystems, where twigs and coarse woody debris significantly contribute to overall carbon stocks (Samariks *et al.*, 2025).

Integrating these contrasting processes, the composition of plant litter, particularly the ratio of leaves to twigs, has a strong influence on both nutrient cycling and carbon storage dynamics in forest ecosystems (Zhang *et al.*, 2024). Maintaining a balance between the rapid nutrient cycling provided by leaves and the long-term carbon storage facilitated by twigs is essential for sustaining ecosystem productivity and biodiversity (Sánchez *et al.*, 2008; Sloboda *et al.*, 2017).

Table 1. Fine litterfall composition in riparian and non-riparian forest

Forest types	Leaves (%)	Twigs (%)	Flowers and inflorescence	Fruits and seeds (%)	Total (%)
Riparian forest	68.61	31.39	0	0	100
Non-riparian forest	78.37	21.30	0	0.33	100

Table 2. Author, land-use, location, fine litterfall biomass, and fine litterfall carbon across the Philippines

Author(s)	Forest type	Location	Fine litterfall Biomass (Mg ha^{-1})	Fine litterfall Carbon (Mg C ha^{-1})
Zaragosa *et al.*, 2016	Secondary forest	Lanao del Norte, Philippines	0.0	0.01
Medina *et al.*, 2020	Secondary forest	Mt. Kiamo, Bukidnon	17.57	9.30
Medina *et al.*, 2020	Secondary forest	Mt. Capistrano, Bukidnon	17.46	7.42
This study	Riparian forest	Carmen, Bohol, Philippines	16.03	8.02
	Non-riparian forest	Carmen, Bohol, Philippines	21.58	10.79

A clearer understanding of the distinct roles of leaves and twigs can guide forest management strategies aimed at improving soil fertility and carbon sequestration. Such strategies may include promoting plant diversity and optimizing litter composition to sustain both nutrient supply and carbon retention (Furey *et al.*, 2021).

Biomass and carbon storage in fine litterfall across forest types

The non-riparian forest in Carmen, Bohol, exhibited significantly higher fine litterfall biomass (21.58 Mg ha^{-1}) and carbon stock (10.79 Mg C ha^{-1}) than the riparian forest (16.03 Mg ha^{-1} and 8.02 Mg C ha^{-1}, respectively; p = 0.029) (Table 2). This difference highlights the influence of hydrological regimes on litter dynamics, as flooding and soil moisture directly affect litter accumulation and decomposition. Supporting this are the studies in other regions that have demonstrated that hydrological variability can significantly influence decomposition rates. In the Sanjiang Plain, China, perennial flooding increased decomposition by 13.41–98.47% compared to seasonal flooding, altering nitrogen (N) and phosphorus (P) dynamics in litter (Sun *et al.*, 2012). Similarly, in the Taihu Lake wetlands, differences in flooding intensity affected the decomposition of *Phragmites australis*, with continuous flooding promoting phosphorus release and nitrogen accumulation after 60 days (Ming-xi, 2011).

Beyond wetland ecosystems, flooding patterns also influence litter decomposition in other environments. In prairie marshes, seasonal flooding accelerated aboveground decomposition by enhancing moisture availability, while belowground decomposition slowed under anoxic conditions (Neckles and Neill, 1994). In the Lake Ontario wetlands, stable hydrological conditions supported higher litter biomass but reduced species density and seedling survival (Vaccaro *et al.*, 2009). Likewise, in the Brazilian Pantanal, seasonal flooding and hydrological fluctuations have been shown to influence litter decomposition and soil respiration, with the addition of litter further enhancing decomposition and carbon cycling (Pinto *et al.*, 2018). In addition to hydrology, the composition of litter nutrients, particularly carbon-to-nitrogen (C/N) and carbon-to-phosphorus (C/P) ratios, strongly regulates decomposition rates. In some wetlands, decomposition positively correlated with C/N ratios under specific flooding regimes (Ming-xi, 2011). Extending this to carbon storage, studies in the Dongting Lake floodplain have shown that seasonal hydrological changes determine whether litter-derived carbon enters the soil organic pool from above- or belowground sources (Zhu *et al.*, 2022).

Collectively, these findings suggest that frequent flooding in riparian areas can remove litter before accumulation, while high moisture accelerates decomposition (Petraglia *et al.*, 2019). Conversely, the relatively stable conditions of non-riparian forests promote litter retention and slower decomposition, resulting in higher biomass and carbon storage (Namaswa, 2025).

Compared to similar ecosystems in the Philippines, the riparian forest values observed here align with those reported for secondary forests in Bukidnon (17.46–17.57 Mg ha^{-1} biomass; 7.42–9.30 Mg C ha^{-1} carbon) (Medina *et al.*, 2020). However, regional variation exists; Zaragosa *et al.* (2016) recorded substantially lower values in Lanao del Norte (0.02 Mg ha^{-1} biomass; 0.01 Mg C ha^{-1} carbon), likely due to differences in forest age, disturbance history, and management practices.

Forest age and successional stage also critically influence litterfall dynamics. In subtropical monsoon evergreen broadleaved forests in Guangdong, China, litterfall production increased along successional gradients, with pioneer forests producing less litter than mature ones (Zhou *et al.*, 2013). Similarly, in the Western Himalaya, litterfall production rose with forest age, reinforcing the link between forest development and nutrient cycling (Joshi and Sundriyal, 2024).

Disturbance events, natural or anthropogenic, similarly affect litterfall. In old-growth *Nothofagus* forests of southern Patagonia, variations in forest structure and productivity were linked to disturbance history, highlighting disturbance as a key driver of litter processes (Amoroso and Blazina, 2020). In Swedish boreal forests, fire and storm events altered species composition and tree dynamics, influencing litterfall (Bradshaw and Hannon, 1992). Anthropogenic pressures in subalpine Western Himalayan forests also reduced litterfall and nutrient return, particularly in broadleaf stands (Gairola *et al.*, 2009).

Forest management intensity and land-use history further modulate litterfall patterns. In temperate forests, higher management intensity has been associated with lower litter mass and nutrient content, suggesting that human intervention affects both litter quantity and quality (Wilcke *et al.*, 2023). Long-term land-use changes in central New England similarly reshaped forest composition and structure, impacting litter production and nutrient cycling (Foster *et al.*, 1998). Finally, regional climatic and edaphic factors refine these dynamics. In the northern Rocky Mountains of the USA, litterfall rates were found to correlate with vegetation characteristics and environmental gradients, including temperature and humidity (Keane, 2008).

In the Dinghushan Biosphere Reserve, temperature and rainfall were significant predictors of litterfall, although the underlying mechanisms remain incompletely understood (Zhou *et al.*, 2013).

Overall, the elevated biomass and carbon values observed in the non-riparian forest likely reflect either a mature, productive ecosystem with efficient nutrient cycling and high carbon sequestration potential (Giweta, 2020; Zhao *et al.*, 2022) or slower decomposition and organic matter accumulation, which could indicate nutrient cycling limitations (Prescott and Vesterdal, 2021).

Structural characteristics and decay dynamics of coarse woody debris

The analysis of coarse woody debris (CWD) in riparian and non-riparian forests of Carmen, Bohol, reveals distinct patterns in abundance, decay stages, and structural characteristics, reflecting the influence of environmental factors on litter accumulation and decomposition. In the riparian forest, 54 CWD pieces were recorded across four decay classes (Table 3), with the majority (57% or 31 pieces) classified as decay class 3. This class was characterized by sound heartwood capable of supporting weight, sapwood that could be pulled apart by hand or was missing, reddish-brown or original wood color, potential root invasion of sapwood, and residual branch stubs that could not be removed (Harmon *et al.*, 2013). Decay class 2 followed (30% or 16 pieces), in which the sapwood was partly soft but not separable by hand; the original wood color remained, no invading roots were observed, and many fine twigs were missing or required peeling of the bark. Only 6% (3 pieces) were in decay class 1, representing freshly fallen, intact logs with no rot. In this forest, mean CWD length increased with decay class: 10.93 m (class 1), 13.95 m (class 2), and 15.32 m (class 3), while mean diameters were 1.63 cm, 4.85 cm, and 4.73 cm, respectively.

Table 3. Decay class category, number of CWD, percentage, mean length, and mean diameter of coarse woody debris (CWD) in riparian and non-riparian forest

Decay class	Riparian forest				Non-riparian forest			
	No. of CWD	Percentage (%)	Mean length (m)	Mean diameter (cm)	No. of CWD	Percentage (%)	Mean length (m)	Mean diameter (cm)
1	3	6	10.93	1.63	10	6	14.76	3.86
2	16	30	13.95	4.85	50	33	18.18	1.94
3	31	57	15.32	4.73	61	40	18.91	3.12
4	4	7	19.16	3.6	32	21	16.1	2.23
5	-	0	-	-	-	-	-	-
Total	54	100	-	-	153	100	-	-

In contrast, the non-riparian forest contained 153 CWD pieces (Table 3), with decay class 3 comprising the largest proportion (40% or 61 pieces). These logs also exhibited sapwood that could be pulled apart or was missing, with reddish-brown or original wood color (Harmon *et al.*, 2013). Decay class 2 followed (33% or 50 pieces), characterized by intact wood color, no invading roots, and fine twigs requiring bark peeling, while early-stage CWD (class 1) represented 6% (10 pieces), with no conks, intact fine twigs, and tight bark. Across all decay classes, mean CWD lengths were longer than those observed in riparian forests: 14.76 m (class 1), 18.18 m (class 2), and 18.91 m (class 3), with mean diameters of 3.86 cm, 1.94 cm, and 3.12 cm, respectively.

These patterns suggest that non-riparian forests generally maintain larger and more abundant CWD, particularly in the early decay stages. This trend likely arises from their more complex forest structure, with larger trees contributing greater volumes of deadwood upon senescence.

Consequently, structural diversity supports a continuous input of CWD, which is essential for sustaining ecosystem processes and biodiversity (Korjus and Laarmann, 2015; Morrissey *et al.*, 2014). Building upon this structural context, the dominant tree species in non-riparian forests frequently possess decay-resistant properties, such as *Quercus* spp., which slow decomposition and promote long-term CWD accumulation (Morrissey *et al.*, 2014).

Furthermore, natural disturbances, including windthrow and insect outbreaks, introduce additional CWD into these forests, creating dynamic conditions where deadwood is continuously replenished, thereby supporting essential ecological functions (Szymañski *et al.*, 2017). In addition to these structural and disturbance factors, non-riparian CWD serves as a moisture reservoir, providing habitat for mycorrhizal fungi that play a critical role in nutrient cycling and tree growth. The high pore volume of downed wood enhances moisture retention, particularly during dry periods (Marcot, 2017).

Beyond these ecosystem functions, CWD also supports a wide range of organisms, including fungi, invertebrates, and vertebrates. The diversity of decay stages and wood sizes fosters rich biodiversity, which is vital for forest resilience (Marcot, 2017; Korjus and Laarmann, 2015). As decomposition progresses, CWD contributes to nutrient cycling and humus formation, enhancing soil fertility and structure, which in turn supports the growth of new vegetation and overall forest health (Marcot, 2017). Finally, the slow decomposition rates of non-riparian forests enable prolonged carbon storage in deadwood, highlighting the role of CWD in carbon cycling and climate change mitigation (Todd and Hanson, 2003).

In contrast, riparian forests exhibit lower CWD abundance, likely due to natural disturbances such as flooding, which remove debris from the forest floor (Sena *et al.*, 2023). Additionally, lower vegetation density, potentially caused by frequent erosion or waterlogging, may limit the accumulation of deadwood (Graziano *et al.*, 2022). At the same time, higher moisture levels in riparian forests create favorable conditions for decay agents, such as fungi, insects, and other organisms, which accelerate decomposition and reduce the persistence of CWD (Manzoni *et al.*, 2023; Zhou *et al.*, 2022).

Collectively, these observations underscore the crucial role of environmental factors, particularly hydrology and vegetation density, in determining the quantity, size, and condition of CWD (Leclerc *et al.*, 2025). Consequently, CWD dynamics influence essential ecosystem functions, including nutrient cycling, carbon storage, and habitat provision. The predominance of intermediate decay classes in both forest types suggests a balance between CWD input and decomposition, although non-riparian forests may provide longer-term carbon storage and more structural habitat due to slower decay and higher retention of early-stage debris.

In conclusion, the composition and structural characteristics of CWD underscore how hydrological regimes, disturbance frequency, and vegetation structure interact to influence decomposition and accumulation patterns in tropical forests. These findings carry important implications for forest management, carbon accounting, and biodiversity conservation, emphasizing the need to consider forest type and environmental conditions when evaluating CWD dynamics. Future studies should quantify CWD biomass and carbon contributions, monitor decomposition over time, and include advanced decay classes to capture the full spectrum of ecosystem processes.

Comparative analysis of CWD biomass and carbon stocks in tropical forests

The coarse woody debris (CWD) biomass (38.24 Mg ha^{-1}) and carbon stock (17.21 Mg C ha^{-1}) of the riparian forest in Carmen, Bohol, were higher than those reported for the seasonal semi-deciduous forest (SSF) in Brazil, which exhibited a biomass of 1.3 Mg ha^{-1} and carbon stock of 0.67 Mg C ha^{-1} (Moreira *et al.*, 2019) (Table 4). Furthermore, the riparian forest's carbon stock exceeded that of a secondary forest in Malaysia (12.3 Mg C ha^{-1}; Yamashita *et al.*, 2022), although it remained lower than that of a Malaysian primary forest (48.8 Mg C ha^{-1}). These comparisons highlight the influence of forest type and structural characteristics on the potential for carbon storage.

Riparian forests often exhibit unique structural features due to their proximity to water bodies, which shape species composition and biomass accumulation. Building upon this observation, the diversity and density of tree species in riparian zones can lead to higher biomass and carbon storage than in other forest types, as evidenced by the Carmen riparian forests (Pereira *et al.*, 2025). In contrast, seasonal semi-deciduous forests in Brazil and secondary forests in Malaysia typically exhibit lower species diversity and density, which contributes to their comparatively reduced biomass and carbon stocks (Maia *et al.*, 2020; Matsuo *et al.*, 2024). Soil fertility and moisture availability further modulate forest biomass and carbon accumulation.

Riparian forests benefit from elevated soil moisture and nutrient availability, which promote tree growth and enhance carbon sequestration (Muller-Landau *et al.*, 2021; Pereira *et al.*, 2025).

Table 4. Authors, land use type, location, CWD biomass, and CWD carbon across the tropical region

Author(s)	Forest type	Location	CWD Biomass ($Mg\ ha^{-1}$)	CWD Carbon ($Mg\ C\ ha^{-1}$)
Moreira *et al.*, 2019	Seasonal semi-deciduous forest (SSF)	State of São Paulo, Brazil	1.3	0.67
Yamashita *et al.*, 2022	Primary forests	Malaysia	Not reported	48.8
Yamashita *et al.*, 2022	Secondary forests	Malaysia	Not reported	12.3
Ekoungoulou *et al.*, 2018	Old growth forest	Africa	Not reported	19.96
Mukul, 2015	Upland secondary Forest	Philippines	Not reported	88.83
This study	Riparian forest	Philippines	38.24	17.21
This study	Non-riparian forest	Philippines	65.58	29.51

Moreover, environmental heterogeneity within riparian zones, including variations in topography and hydrology, generates microhabitats that support diverse plant communities and higher biomass accumulation (Pereira *et al.*, 2025). Conversely, seasonal semi-deciduous forests in Brazil may experience prolonged dry periods, which limit tree growth, biomass accumulation, and carbon storage (Maia *et al.*, 2020).

As a result of these favorable conditions, riparian forests exhibit significant potential for rapid carbon sequestration due to their diverse species, structural complexity, and resource-rich environments. This makes them valuable not only for carbon offset initiatives but also for sustaining broader ecosystem services (Dybala *et al.*, 2019). Consequently, the higher carbon stocks observed in riparian forests relative to secondary forests underscore the importance of conserving and restoring these ecosystems to maximize their carbon sequestration potential (Dybala *et al.*, 2019; Nagy *et al.*, 2015). Ultimately, understanding the drivers of carbon storage across different forest types is crucial for guiding conservation and restoration strategies, particularly in regions threatened by deforestation and land-use change (Fonsêca *et al.*, 2024).

Carbon storage and ecological functions of coarse woody debris

The non-riparian forest exhibited significantly higher CWD biomass (65.58 $Mg\ ha^{-1}$) and carbon stock (29.51 $Mg\ C\ ha^{-1}$) compared to the riparian forest, which had an average biomass of 38.24 $Mg\ ha^{-1}$ and carbon stock of 17.21 $Mg\ C\ ha^{-1}$ ($p = 0.00$) (Table 5). This higher CWD in non-riparian forests can be attributed to stable environmental conditions that support larger, older trees, which in turn enhance the abundance, diversity, and productivity of littoral biota by providing shelter and moderating predator-prey interactions (Czarnecka, 2016). Furthermore, late-successional non-riparian forests exhibit increased CWD mass and more advanced decay stages, further contributing to long-term carbon sequestration (Lee and Choung, 2024).

In contrast, riparian forests, while exhibiting lower total carbon storage, are efficient in carbon retention per unit biomass. Large woody debris in freshwater environments can enhance carbon storage, although its contribution remains poorly quantified (Wohl, 2024). Riparian zones, however, are subject to disturbances such as flooding, which reduce CWD retention and limit their overall carbon storage capacity (Mohan and Joseph, 2024). Despite these constraints, riparian forests play a crucial role in carbon cycling and maintaining ecosystem function (Ruffing *et al.*, 2016).

Beyond carbon storage, riparian forests provide essential ecosystem services. They regulate water flow, reduce soil erosion, and supply organic matter to streams, supporting diverse aquatic and terrestrial biota (Graziano *et al.*, 2022). Biodiversity in these zones further enhances ecological processes such as nutrient cycling and decomposition, contributing to the overall health of coupled aquatic-terrestrial systems (Oester *et al.*, 2024). Consequently, even with lower total carbon stocks, riparian forests remain crucial for sustaining ecosystem function and resilience in the face of global environmental change (Bambi *et al.*, 2022; Guo, 2015).

Table 5. Biomass and carbon stock of riparian and non-riparian forests

Plot No.	Riparian		Non-riparian	
	Biomass (Mg ha-1)	Carbon Stock (Mg C ha -1)	Biomass (Mg ha-1)	Carbon Stock (Mg C ha -1)
1	41.04	18.47	48.82	21.97
2	69.61	31.33	181.35	81.61
3	66.38	29.87	9.60	4.32
4	3.25	1.46	38.74	17.43
5	25.54	11.49	39.01	17.55
6	6.09	2.74	65.16	29.32
7	13.89	6.25	87.42	39.34
8	80.09	36.04	54.47	24.51
Average	38.24	17.21	65.57	29.50

Although non-riparian forests store more carbon overall, both forest types are efficient at carbon retention per unit biomass, with observed differences largely driven by environmental conditions (Chen *et al.*, 2024). Factors such as hydrological regimes and disturbance frequency strongly influence CWD dynamics and ecosystem services across forest types. For example, hardwood floodplain forests show variable carbon stocks depending on forest age and hydrological conditions (Shupe *et al.*, 2021).

Effective forest management can further enhance these ecosystem functions. Practices such as selective thinning in riparian forests can promote biodiversity and structural complexity, supporting long-term ecological benefits (Pollock and Beechie, 2014). Additionally, understanding the legacy of past disturbances, including logging, is essential for assessing impacts on carbon storage and ecosystem processes, thereby informing sustainable management and conservation strategies (McGarvey *et al.*, 2015).

CONCLUSION

This study demonstrates that both fine litterfall and coarse woody debris (CWD) are significant contributors to carbon storage in riparian and non-riparian forests of Carmen, Bohol. Fine litterfall, dominated by leaves and supplemented by twigs, provides a rapid source of organic matter and essential nutrients that enhance soil fertility and forest productivity. In contrast, CWD functions as a long-term carbon reservoir and structural habitat, supporting forest resilience and sustaining biodiversity over extended periods. Comparatively, non-riparian forests store higher carbon in both fine litterfall and CWD than riparian forests, likely due to differences in tree composition, stand age, and decomposition dynamics. Nonetheless, riparian forests play a crucial role in regulating ecosystem processes, including nutrient cycling and hydrological balance, which indirectly influence carbon dynamics and maintain ecosystem function. Taken together, these findings emphasize the importance of considering both fine litterfall and CWD when estimating forest carbon stocks, as each component contributes complementary roles in carbon sequestration and ecosystem sustainability. Accurate quantification of these litter components is therefore essential for guiding forest management, informing conservation planning, and supporting climate change mitigation strategies in tropical forest landscapes. In conclusion, integrating assessments of fine litterfall and CWD provides a more comprehensive understanding of forest carbon dynamics, underscoring the importance of conserving both riparian and non-riparian forests to optimize carbon storage and sustain vital ecosystem functions.

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