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Necromass Carbon Stock in a Secondary Atlantic Forest Fragment in Brazil

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Abstract: Necromass has a relevant role to play in the carbon stock of forest ecosystems, especially with the increase of tree mortality due to climate change. Despite this importance, its quantification is often neglected in tropical forests. The objective of this study was to quantify the carbon storage in a secondary Atlantic Forest fragment in Viçosa, Minas Gerais, Brazil. Coarse Woody Debris (CWD), standing dead trees (snags), and litter were quantified in twenty 10 m x 50 m plots randomly positioned throughout the forest area (simple random sampling). Data were collected during 2015, from July to December. The CWD and snags volumes were determined by the Smalian method and by allometric equations, respectively. The necromass of these components was estimated by multiplying the volume by the apparent density at each decomposition classes. The litter necromass was estimated by the proportionality method and the average of the extrapolated estimates per hectare. The carbon stock of the three components was quantified by multiplying the necromass and the carbon wood content. The total volume of dead wood, including CWD and snag, was 23.6 ± 0.9 m^3 ha^{-1}, being produced mainly by the competition for resources, senescence, and anthropic and climatic disturbances. The total necromass was 16.3 ± 0.4 Mg ha^{-1}. The total carbon stock in necromass was 7.3 ± 0.2 MgC ha^{-1}. The CWD, snag and litter stocked 3.0 ± 0.1, 1.8 ± 0.1, and 2.5 ± 0.1 MgC ha^{-1}, respectively. These results demonstrate that although necromass has a lower carbon stock compared to biomass, neglecting its quantification may lead to underestimation of the carbon balance of forest ecosystems and their potential to mitigate climate change.

Keywords: climate change; coarse woody debris; litter; rainforest; snags; dead organic matter

1. Introduction

The Atlantic Forest is the most degraded biome in Brazil with most of its remaining forest fragments being smaller than 50 ha [1–3]. The main driver responsible for this fragmentation was the pressure exerted by human activities, such as agriculture, logging, and urban growth [4–6]. These activities together with climate change have affected forest dynamics, altering carbon storage and the tree mortality rate [7–9].

This increase in tree mortality leads to a greater accumulation of necromass (dead organic matter) that can remain on tropical forest soil for more than 30 years [10]. Necromass plays a key role during this phase of the forest ecosystem, providing food for saproxylic organisms [11,12], habitat for invertebrates and vertebrates [13], integration of forest nutrient cycling [14,15], and storing carbon [16–18].

Necromass is estimated to be responsible for stocking 73.0 ± 6.0 PgC, representing 8% of the world's forest carbon [19]. In Brazil, Forest Resource Assessments (FRA) estimated a carbon stock in the necromass of 1.94 PgC, including Coarse Wood Debris (CWD), standing dead trees (Snags), and litter. Of this total, approximately 6.3% is contained in the Atlantic Forest biome [20].

Despite the importance of necromass, its quantification is often neglected in Atlantic forests, thereby underestimating carbon stock estimates in these forests [21,22]. Therefore, this paper seeks to address this research gap by quantifying the necromass in different categories (CWD, snags, and litter), decomposition classes and carbon content in an Atlantic Forest. In addition, we analyze the contribution of these categories in different diameter classes. The purpose of this study therefore, was to show the importance of necromass in carbon storage in a secondary Atlantic Forest fragment in Viçosa, Minas Gerais, Brazil.

2. Materials and Methods

2.1. Description of the Study Area

The forest fragment is located in the Technological Park of Viçosa in Viçosa, Minas Gerais, Brazil (42°51′ W and 20°42′ S) (Figure 1) and has 44.11 ha. The local climate is Cwa (Köppen classification) with temperature, humidity and annual precipitation averages of 21.9 °C, 79%, and 1.274 mm, respectively [23]. The region has pedogeomorphologic gradients with aluminum-rich dystrophic latosols at the tops of hills, colluvial ramps with shallow latosols and cambic horizon, while the bottoms of the groves present a predominance of epieutrophic cambisols rich in nutrients [24].

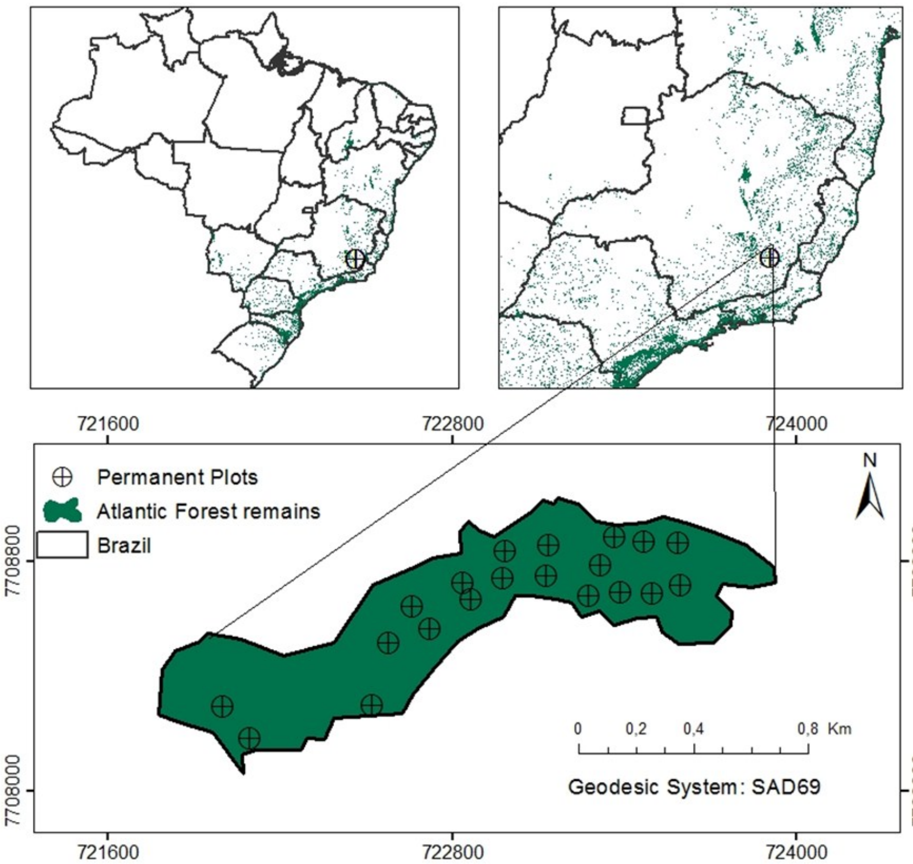

Figure 1. Location of the secondary Atlantic Forest fragment and distribution of permanent plots in the area.

The vegetation of the region is classified as seasonal semideciduous forest [25] in the middle stage of regeneration presenting woody species with a diameter at breast height (DBH) of 10 to 20 cm and a height of 5 to 12 m [26]. Phytosociological parameters, floristic composition and forest dynamic were quantified in 2010 and 2015 (Table 1). Several disturbances have occurred in this forest fragment over the years, such as the removal of timber of commercial value and the planting of agricultural and forestry crops. However, the forest fragment has been regenerating for approximately 30 years [27].

Table 1. Phytosociological parameters, floristic composition, and forest dynamic of the secondary Atlantic Forest fragment.

Variable	Year of Measurement	
	2010	**2015**
Botanical Families	43	47
Botanical Genera	98	102
Identified Species	127	134
Non - Identified Species	3	5
Shannon-Weaver Index (H′)	3.97	4.01
Density (stems ha^{-1})	1,526	1,692
Quadratic mean diameter (cm)	12.27	12.31
Basal Area (m^2 ha^{-1})	18.05	20.15
Minimum DBH (cm)	5.03	5.01
Arithmetic mean diameter (cm)	10.47	10.52
Maximum DBH (cm)	65.57	50.29
Minimum Height (m)	3.00	3.00
Average Height (m)	10.08	11.17
Maximum Height (m)	30.00	34.50
Volume (m^3 ha^{-1})	128.12	152.04
Aboveground biomass (Mg ha^{-1}) *	86.23	102.71
Carbon stock in aboveground biomass (MgC ha^{-1})	40.01	47.64
Forest Dynamic	**2010–2015**	
Recruited Stems (stems ha^{-1})	335	
Mortality Stems (stems ha^{-1})	169	
Carbon stock in Recruitment (MgC ha^{-1})	1.66	
Carbon stock in Mortality (MgC ha^{-1})	3.72	
Gross increment in Carbon (MgC ha^{-1}) **	9.69	

* Aboveground biomass includes branches, leaves and stems with DBH ≥ 5 cm; ** The Gross Increment (GI) in carbon was obtained through the equation GI = (Cf – R) – (Ci – M), where: GI = gross increment, excluding the recruitment (MgC ha^{-1}); Cf = carbon stock in 2015 (MgC ha^{-1}); Ci = carbon stock in 2010 (MgC ha^{-1}); R = recruitment of stems, resulting in the carbon growth (MgC ha^{-1}); M = mortality of stems, resulting in carbon loss (MgC ha^{-1}).

2.2. Quantification of Volume, Necromass and Carbon Stock

Coarse Woody Debris (CWD), standing dead trees (snags), and litter were quantified in twenty 10 m × 50 m plots, randomly positioned throughout the forest area (simple random sampling). Data were collected during 2015, from July to December.

Branches, stumps and trees fallen on the soil with DBH ≥ 5 cm were considered CWD and, according to their decomposition stage, divided into four classes [28,29]: (1) newly fallen to the soil with leaves and tree bark intact; (2) residues similar to those in class 1 but with tree bark showing rot or scaling; (3) residue at an advanced stage of decomposition with some resistance to being broken; (4) rotten and friable residues with no resistance when broken.

The CWD volume (mean ± standard deviation) was determined using the Smalian method considering the diameter at the ends of each section and the length of dead wood [30]. The necromass (mean ± standard deviation) was estimated by multiplying the volume and apparent density, in the four decomposition classes [31]. Eighty samples per decomposition class were collected from the twenty plots to determine the apparent density of deadwood. The apparent density was determined by mercury immersion method, due to material fragility [32,33]. The mean densities were compared by Tukey's test, at 5% probability, using software R [34].

The carbon stock (mean ± standard deviation) was estimated by multiplying the necromass and carbon content of dead wood. The dead wood carbon content from the first and second decomposition classes was quantified in wood samples from three live trees, separated by species and diameter class, and the other classes, with wood samples taken from the woody residues in the soil. The carbon content of deadwood was quantified by the calcination method using a Linn Elektro Therm muffle furnace. Composite samples of approximately 1g were oven dried at 105 °C and placed in the muffle in porcelain crucibles. The temperatures used in the calcination process were 200 °C (for 1 hour), 400 °C (for 2 hours), and 550 °C (for 3 hours). After cooling, the crucibles with ash were weighted and percentage of carbon content (C%) was calculated by the expressions [35]: Ash (%) = $(W_3 - W_1)/(W_2 - W_1) \times 100$ and C (%) = (100 − Ash%) × 0.50, where: W_1 = the weight of crucibles; W_2 = the weight of oven dried ground samples crucibles; W_3 = the weight of ash + crucibles; and 0.50 = the content of carbon in the organic matter [36,37].

The snags included standing dead trees with DBH ≥ 5 cm, without branches, leaves and/or bark. The diameter at breast height (DBH) and total height were measured for this component. The snags volume (mean ± standard deviation) was quantified with equation: $Vs = 0.000044 \times DBH^{2.064540} \times H^{0.830779}$, where: Vs = volume of the stem, in m^3; DBH = diameter at breast height, in cm; and H = total height, in m [38]. The snags aboveground necromass and the carbon stock (mean ± standard deviation) were quantified from the mean densities of four classes of CWD decomposition and the carbon content of the live trees, respectively.

The dead wood with DBH ≤ 5 cm, leaves, flowers, and fruits were included in the litter evaluation. Two subplots of 1 m^2 were allocated per plot and the collected material was taken to a forced air circulation oven at approximately 65 °C until weight stabilization. The dry mass (mean ± standard deviation) was obtained using the proportionality method: DM(f) = (WM(f) × DM(s)/WM(s)), where: DM(f) = total dry matter mass in the field, in kg; WM(f) = total wet matter mass in the field, in kg; DM(s) = dry matter mass of the samples, in kg; and WM(s) = wet mass of the samples, in kg [39]. The average of DM(f) estimates was extrapolated to the hectare and multiplied by the carbon content to determine the carbon stock of this component (mean ± standard deviation). Carbon content was determined using the same procedure as CWD.

3. Results

The CWD volume of the four decomposition classes was 14.8 ± 0.6 m^3 ha^{-1}, the snags volume was 8.8 ± 0.7 m^3 ha^{-1} and the total dead wood volume was 23.6 ± 0.9 m^3 ha^{-1}, being higher in the first diameter classes (Figure 2).

The apparent density and carbon content for the quantification of necromass and carbon stock, respectively, varied according to the type of component and the decomposition class of the dead wood (Table 2).

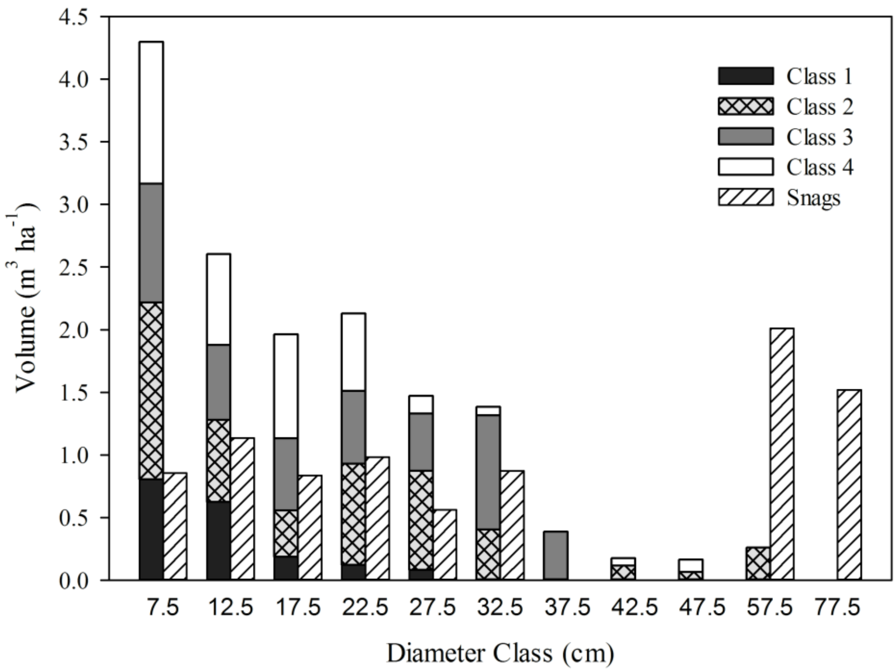

Figure 2. Coarse Woody Debris (CWD) and Snags volume, in m^3 ha^{-1}, by diameter class and decomposition classes. Decomposition classes: (1) newly fallen to the soil with leaves and tree bark intact; (2) residues similar to those in class 1 but with tree bark showing rot or scaling; (3) residue at an advanced stage of decomposition with some resistance to being broken; (4) rotten and friable residues with no resistance when broken.

Table 2. Apparent density – (Dens.) (mean ± standard deviation), carbon content – (Carbon Cont.) (mean ± standard deviation) and variation range – (Var. Ran.) of the CWD, snags, and litter.

Dead Wood	Class. of Decomp.	Dens. (g cm^{-3})	Var. Ran. (g cm^{-3})	Carbon Cont. (%)	Var. Ran. (%)
CWD	1	0.577 ± 0.128 a	0.358 – 0.913	45.49 ± 0.76	42.80 – 47.54
	2	0.527 ± 0.167 a	0.234 – 0.865		
	3	0.395 ± 0.108 b	0.172 – 0.650	45.44 ± 1.31	43.25 – 46.63
	4	0.321 ± 0.165 c	0.128 – 0.796		
Snags	-	0.455 ± 0.174	0.128 – 0.913	45.49 ± 0.76	42.80 – 47.54
Litter	-	-	-	44.46 ± 2.83	33.00 – 47.25

Means followed by the same letter do not differ at 5% by Tukey's test. Decomposition classes: (1) newly fallen to the soil with leaves and tree bark intact; (2) residues similar to those in class 1 but with tree bark showing rot or scaling; (3) residue at an advanced stage of decomposition with some resistance to being broken; (4) rotten and friable residues with no resistance when broken.

The total necromass in the forest fragment was 16.3 ± 0.4 Mg ha^{-1}. Of this total, 6.6 ± 0.3 Mg ha^{-1} corresponds to CWD, 4.0 ± 0.3 Mg ha^{-1} to snags and 5.7 ± 0.1 Mg ha^{-1} to litter. The carbon stock of components (CWD, snags and litter) was 3.0 ± 0.1 MgC ha^{-1}, 1.8 ± 0.1 MgC ha^{-1} and 2.5 ± 0.1 MgC ha^{-1}, respectively, reaching a total carbon stock of 7.3 ± 0.2 MgC ha^{-1} (Figure 3).

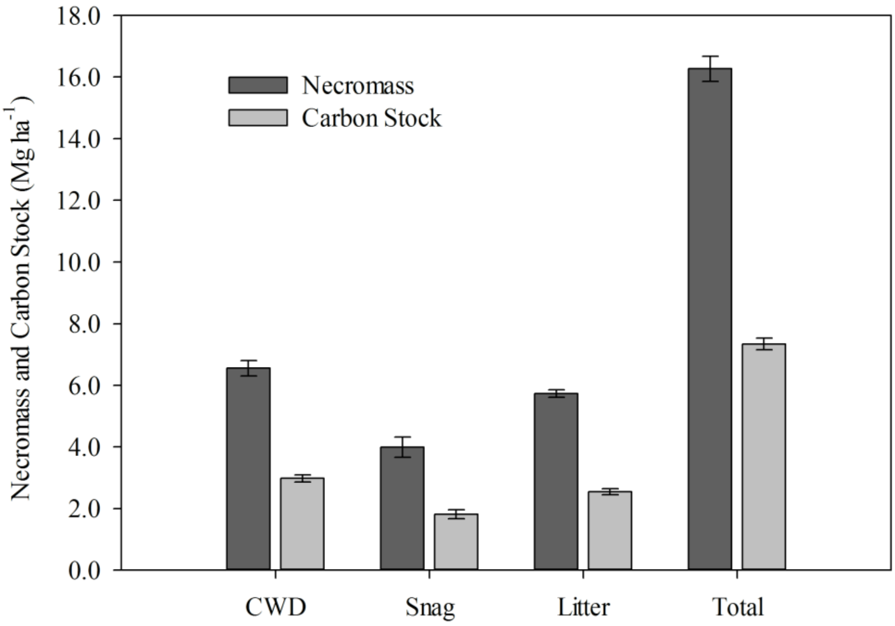

Figure 3. Necromass and carbon stock (Mg ha^{-1}) of the CWD, snags, litter, and total of the secondary Atlantic Forest fragment.

4. Discussion

The necromass produced via the growth dynamics of tropical forests represents an essential element in biogeochemical cycles because it acts as a source of carbon for the atmosphere and soil [14,40,41]. Its quantification is necessary to express temporal changes in carbon stocks, reducing uncertainties about their ability to mitigate climate change while present in the forest ecosystem [42,43].

The higher volume of dead wood (CWD and Snag) in the 7.5 to 22.5 cm diameter classes (Figure 2) shows that trees with smaller diameters are more susceptible to mortality, mainly due to competition for water, light and nutrients [44–46]. In the forest fragment evaluated, the mortality of stems in these diameter classes between 2010 and 2015 represented 98% of the total mortality (Figure S1 and Table 1), contributing 62.68% of the volume of necromass produced. On the other hand, mortality of larger diameter stems was less frequent in the forest fragment (Figure S1). Despite this low mortality, the volume of necromass with DBH > 22.5 cm represented 37.32% of the total necromass produced. It is expected that with the forest successional advance there is an increase in tree mortality due to senescence [47–49], although other factors such as anthropogenic disturbances [50] or climatic disturbances such as heavy rainfall [44,51], extreme drought [9,52], and El Niño [53] can also boost tree mortality. In addition, the increased presence of necromass in later stages of decomposition indicates that tree mortality may have occurred at more distant times. This fact highlights the need to carry out more frequent forest inventories and to monitor the phytosanitary conditions of the trees while alive to determine more precisely when a tree dies [54].

The estimated necromass for CWD, snags, and litter were 40.49%, 24.54%, and 34.96%, respectively, in relation to the total necromass produced (16.3 ± 0.4 Mg ha^{-1}) in the forest fragment. Studies conducted in Atlantic forests estimated a lower necromass than that found in the forest fragment evaluated, ranging from 6.7 Mg ha^{-1} [55] to 14.1 Mg ha^{-1} [56]. This lower estimate for the necromass can be explained by the failure to quantify components such as snags and litter, underestimating the dead organic matter of forests. In addition to production, the different bulk density values used for each component and decomposition class of deadwood (Table 2) help explain the variation between necromass estimates. The use of fixed density values could cause distortions in necromass estimates in a forest [31,57]. Thus, the density values found in this study may support future research to more accurately estimate the necromass of Atlantic Rainforest.

In the carbon content, a small variation was observed between the components (CWD, snag, and litter) and decomposition classes (Table 2). We did not find correlation between necromass decay class and its carbon content, as noted by Moreira et al. [57]. Despite that it is important to do further research analyzing in detail the carbon content in each forest floor compartment [58] and decomposition classes [31] to ensure better accuracy of carbon stock estimates [59,60].

The necromass carbon stock (7.3 ± 0.2 MgC ha^{-1}) represented 13.4% of the aboveground carbon in this forest fragment. The importance of necromass in carbon storage has also been reported in other tropical forests, ranging from 11.3% [61] to 17.0% [62] of total aboveground carbon stock. This variation of the carbon stock contribution to the necromass can be explained by the floristic composition, structure and elevation gradient of the forests. It should be noted that, although necromass has a lower carbon stock in relation to biomass, neglecting its quantification might lead to underestimation of the forest ecosystem carbon balance and its potential to mitigate climate change [63,64].

5. Conclusions

Necromass found in the secondary Atlantic Forest can store large amounts of carbon and should be included in studies that aim to quantify the forest ecosystem carbon balance. Omitting the CWD, snags or litter quantification may lead to a carbon stock underestimation due the relative importance of each necromass component. The methodology used in this study can be replicated in other forests around the world, and can be used in the Forest Resource Assessments (FRA) carried out by specific countries, producing more precise necromass carbon estimates. Future research should focus on knowledge of necromass production dynamics and their proper management so that the decomposition of these materials is minimized.

Supplementary Materials: The following are available online at http://www.mdpi.com/1999-4907/10/10/833/s1, Figure S1. (A) Density (stems ha^{-1}) of live trees; (B) Carbon Stock (MgC ha^{-1}) of live trees; (C) Stems died (stems ha^{-1}) in the period 2010–2015; and (D) Carbon Stock (MgC ha^{-1}) of dead trees in the period 2010–2015.

Author Contributions: Conceptualization, C.M.M.E.T.; Investigation, P.H.V.; Project administration, C.M.M.E.T.; Validation, L.A.G.J., C.P.B.S. and L.F.d.S.; Writing—original draft, P.H.V.; Writing—review & editing, C.M.M.E.T., L.A.G.J., C.P.B.S., L.Fd.S., B.L.S.S., S.J.S.S.d.R. and J.C.Z.

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Conflicts of Interest: The authors declare no conflict of interest.

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