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Impacts of a severe storm on carbon accumulation in coarse woody debris within a secondary Atlantic Forest fragment in Brazil

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Abstract The alarming increase in extreme weather events, such as severe storms with torrential rain and strong winds, is a direct result of climate change. These events have led to discernible shifts in forest structure and the carbon cycle, primarily driven by a surge in tree mortality. However, the impacts caused by these severe storms on the production and carbon increment from coarse woody debris (CWD) are still poorly understood, especially in the Brazilian Atlantic Forest. Thus, the goal proposed by the study was to quantify the CWD volume, necromass, and carbon stock before and after the occurrence of a severe storm and to determine the importance of spatial, structural, and qualitative variables of trees in the CWD carbon increment. The increase in carbon by the storm was 2.01 MgC ha^{-1}, with a higher concentration in the CWD less decomposed and smaller diameter class. The forest fragment plots showed distinct increments (0.05–0.35 MgC), being influenced by spatial (elevation, declivity, and slope angle) structural (basal area) and qualitative factors (trunk quality and tree health), intrinsic to the forest. Thus, it is concluded that severe storms cause a large increase in carbon in CWD, making it essential to understand the susceptibility of forests to the action of intense rains and strong winds to model and monitor the future impacts of these extreme weather events on Atlantic Forest and other tropical forests in the world.

Keywords Necromass · Tree mortality · Climate changes · Extreme weather events

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Introduction

Extreme weather events have been increasingly frequent due to climate change (Neumann et al., 2017; O'Neill et al., 2017; Taccoen et al., 2021). Storms with intense rains and strong winds, for example, have been observed in recent years, causing changes in the forests structure and the carbon cycle due to increased tree mortality (Aleixo et al., 2019; Chao et al., 2022; Crockett & Westerling, 2018; Klein & Hartmann, 2018; Taccoen et al., 2019). In tropical forests, mortality from severe storms is estimated to cause carbon reductions in aboveground living biomass on

the order of approximately 1.7 PgC year^{-1} (Espírito-Santo et al., 2014a; Silvério et al., 2019).

The impacts generated by these events on tree mortality are influenced by storm strength (Canham et al., 2010), topography (de Toledo et al., 2012), forest structure (Schwartz et al., 2017), and the trees' qualitative, physical, and anatomical characteristics (Rifai et al., 2016). The way in which these variables interact during the event determines the damage severity caused to trees, ranging from crown or trunk breakage or even the toppling of entire trees (Chao et al., 2009; de Toledo et al., 2013; Fontes et al., 2018).

All these types of damage caused to trees increase the coarse wood debris (CWD) production, impacting the carbon cycle (Lladó et al., 2017; Malhi et al., 2011). Initially, CWD accumulates under the forest floor, storing substantial amounts of carbon (Köhl et al., 2015). It is estimated that the carbon enclosed within CWDs may endure retention for over 30 years in tropical climate forests (Barbosa et al., 2017; Yizhao et al., 2015). In subsequent phases, this carbon can be incorporated into the soil (dos Santos et al., 2016) or returned to the atmosphere due to the decomposition process (Brienen et al., 2015; Harmon et al., 2020). This carbon loss can potentially be offset by the recruitment and growth of remaining trees (Chambers et al., 2004).

While there exists a comprehensive understanding of tree damage and carbon cycle, the impact of severe storms on CWD production and carbon stock remains insufficiently investigated, especially within the ecosystem of the Atlantic Forest (Espírito-Santo et al., 2014a, b). This knowledge gap is significant due to the unique ecological characteristics of the Atlantic Forest, coupled with its susceptibility to extreme weather events (Bellard et al., 2014; Scarano & Ceotto, 2015).

A factor contributing to this limited knowledge is the stochastic nature of extreme weather events, which makes it difficult to predict when they will occur (Cushman et al., 2021; Ye et al., 2021). Another challenging factor is the understanding of the carbon stock existing in the CWD before the occurrence of the storm. Generally, necromass forest inventories are carried out once and using temporary sampling methods (Maas et al., 2020; Moreira et al., 2019; Russell et al., 2015), without recording the identity of the CWD that were measured. However, this type of approach makes it difficult to understand possible

changes in the CWD carbon stock over time (Gora et al., 2019; Palace et al., 2012). Therefore, the use of permanent plots with the prior identification of CWD measured before the occurrence of the storm is essential to have accurate estimates of the impact of storms on the CWD carbon increment (Campbell et al., 2019; Gora et al., 2019; Villanova et al., 2019).

This study was conducted following these guidelines, with CWD being identified and measured in permanent plots before and after the occurrence of a severe storm in the municipality of Viçosa (Minas Gerais State, Brazil), which impacted fragments of seasonal semideciduous forests in the region (Emerick & Martini, 2020; INMET, 2021). Thus, the goal proposed for the study were (i) quantify the CWD volume, necromass, and carbon stock before and after the occurrence of a severe storm to determine the impacts of this extreme climatic event on the increment of these parameters and (ii) determine the importance of spatial, structural, and qualitative variables of trees in the CWD carbon increment.

Material and methods

Study area

The research was conducted within a 17-ha secondary fragment of Atlantic Forest, referred to as "Mata da Silvicultura," situated in Viçosa, Minas Gerais State, Brazil (Fig. 1). The area has pedogeomorphological gradients, featuring aluminum-rich dystrophic latosols at hilltops, colluvial ramps with shallow latosols, and cambic horizons, while the lower areas of the groves are characterized by a prevalence of nutrient-rich epieutrophic cambisols (Ferreira Junior et al., 2012). The topographic characteristics, including declivity, slope angle, and elevation (Table A1 and Fig. A1), were characterized using digital elevation models developed by the Topodata project (INPE, 2011), which provides refined data from the Shuttle Radar Topography Mission (SRTM) for the Brazilian region (Valeriano & Rossetti, 2012).

The vegetation in the area falls under the classification of seasonal semideciduous forest (IBGE, 2012). The studied forest fragment is currently in an intermediate stage of regeneration (da Rocha et al., 2020), where the quadratic mean diameter and total height of trees range from 10 to 20 cm and 5 to 12

Fig. 1 Location of the studied Atlantic Forest fragment. Figure adapted from Villanova et al. (2023). The map was generated using QGIS 3.10.6—http://qgis.osgeo.org (QGIS.org, 2020)
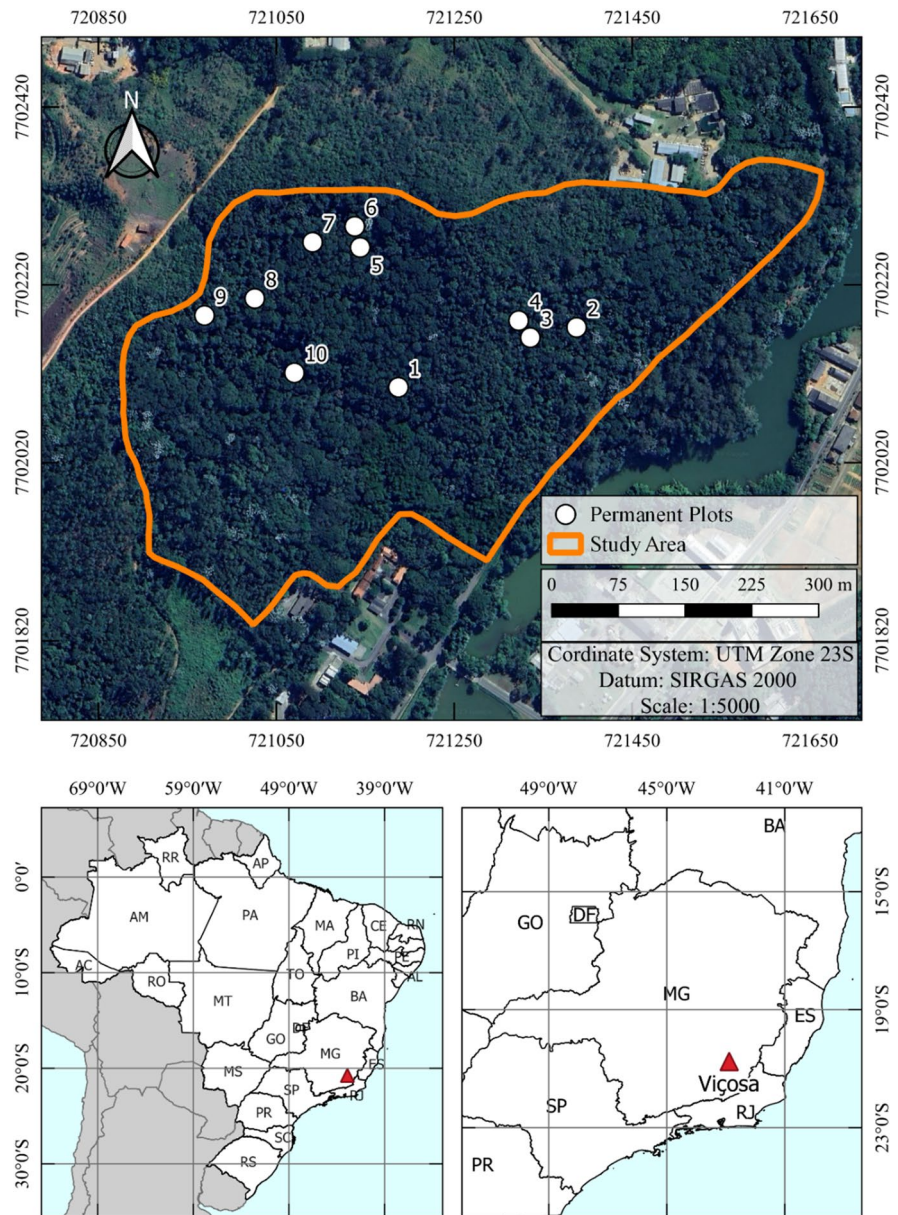
m, respectively (Brasil, 2007). A forest inventory was executed in 2016. We measured all standing trees with a diameter at breast height (dbh) ≥ 5 cm (Table 1). Subsequently, we calculate the floristic composition, phytosociological parameters, and dendrometric variables.

The study site experiences a Cwa climate classification according to Köppen's system, characterized by an average temperature of 19.9°C, humidity levels of 79.9%, and an annual average precipitation of 1269.4 mm (UFV, 2021). The severe storm considered in

this study occurred on October 25, 2019 (Emerick & Martini, 2020). The strongest wind gusts reached 82.40 km h^{-1} and their directions varied between south-southeast, south-southwest, and west-southwest (Emerick & Martini, 2020). The precipitation recorded during the first hour of this extreme weather event was 67 mm. The accumulated rainfall for the 5-h period was 112.4 mm (INMET, 2021), exceeding the historical average of precipitation for the reference month recorded between the years 1968 to 2019 (Fig. 2). Given these numbers, this severe storm can

Table 1 Floristic composition, phytosociological parameters and dendrometric variables, per plot, of "Mata da Silvicultura" in 2016. Plots size: 20 m × 50 m (0.1 ha)

Variables	Plots									
	1	2	3	4	5	6	7	8	9	10
Botanical families	22	26	23	21	21	18	23	15	28	21
Botanical genera	38	45	37	37	33	32	38	29	45	40
Identified species	147	141	130	123	93	108	120	160	192	132
Pioneers	6	34	15	20	7	6	6	3	13	12
Initial secondary	121	79	90	71	70	86	97	128	147	80
Late secondary	26	28	25	32	16	16	17	29	32	40
Non-identified species	6	6	5	10	1	5	5	4	7	16
Shannon-Weaver Index (H′)	3.07	3.26	3.47	3.51	2.96	3.06	3.19	2.78	3.26	3.43
Density (stems per plot)	160	149	136	137	95	116	125	166	200	148
Basal area (m^2 per plot)	3.52	2.49	2.08	2.02	1.61	2.95	5.13	3.31	3.00	3.26
Quadratic mean diameter (cm)	16.7	14.6	13.9	13.7	14.7	18.0	22.9	15.9	13.8	16.7
Minimum DBH (cm)	5.1	5.1	5.0	5.0	5.0	5.0	5.0	5.1	5.0	5.0
Maximum DBH (cm)	94.2	46.5	35.0	38.8	57.9	81.8	87.9	58.9	55.3	84.4
Average height (m)	12.2	13.1	13.0	12.9	11.9	13.8	14.9	13.3	11.2	12.0
Minimum height (m)	4.0	2.6	4.3	3.7	2.8	3.3	3.9	3.8	4.5	2.4
Maximum height (m)	33.6	34.0	27.0	25.6	33.0	33.6	38.0	33.0	34.5	30.7

be considered an extreme weather event, as defined by the Intergovernmental Panel on Climate Change (IPCC) (Field et al., 2012).

After the severe storm, various damage was detected in the municipality of Viçosa (Emiliana & Bottrel, 2019; Maior, 2019; Prefeitura de Viçosa, 2019). In the studied forest fragment, many trees died uprooted or broken due the winds gusts and heavy rain, leading to the formation of gaps in the forest canopy and the accumulation of necromass above the forest floor (Fig. 3).

Data collection

Coarse woody debris (CWD), including branches, stumps, and fallen trees with a diameter greater than or equal to 5 cm, was inventoried in ten permanent plots measuring 20 m × 50 m. The CWD was sorted into diameter classes with a 5-cm interval and further categorized into four classes based on their decomposition stage (Harmon et al., 1995; Keller et al., 2004; Villanova et al., 2019, 2023): (DC1) materials recently fallen to the forest floor, with leaves and bark intact; (DC2) materials similar to those in class "DC1," but exhibiting signs of bark decay or peeling; (DC3) materials in an advanced state of decomposition, displaying some resistance to breakage; (DC4)

materials that are highly decayed and friable, lacking resistance to breakage.

CWD inventories were carried out at two times: before and after the occurrence of the severe storm. The pre-storm inventory took place between August and October 2019, ending on October 23, 2019 (Wednesday, 2 days before the storm). All CWD found inside the plots were marked with plastic platelets to identify the residues measured at that first occasion. The second inventory was carried out immediately after the storm, between the months of October and November 2019, starting on October 26, 2019 (Saturday, 1 day after the storm). In this case, only those residues that had not been identified by plastic platelets in the first inventory were measured, making it possible to quantify the CWD accumulation due to the storm occurrence.

Volume, necromass, and carbon stock quantification

The apparent density and carbon content were assessed following the methodology outlined by Villanova et al. (2023). Apparent density (g cm^{-3}) was determined through mercury immersion, adopting the procedure by Vital (1984) and ABNT (2003). Meanwhile, carbon content (%) was analyzed using a dry combustion elemental analyzer (LECO TruSpec® Micro Elemental Series CHN/CHNS/O; St. Joseph,

Fig. 2 Viçosa's climogram indicating the average temperature and precipitation, by month, for the years 1968 to 2019 (**A**) and 2019 (**B**). The white bar indicates the monthly precipitation and the blue bar indicates the severe storm that represented, approximately 80% of the monthly precipitation in a single day. The red line represents the average temperature and the confidence region shaded in light red corresponds to the maximum and minimum temperatures
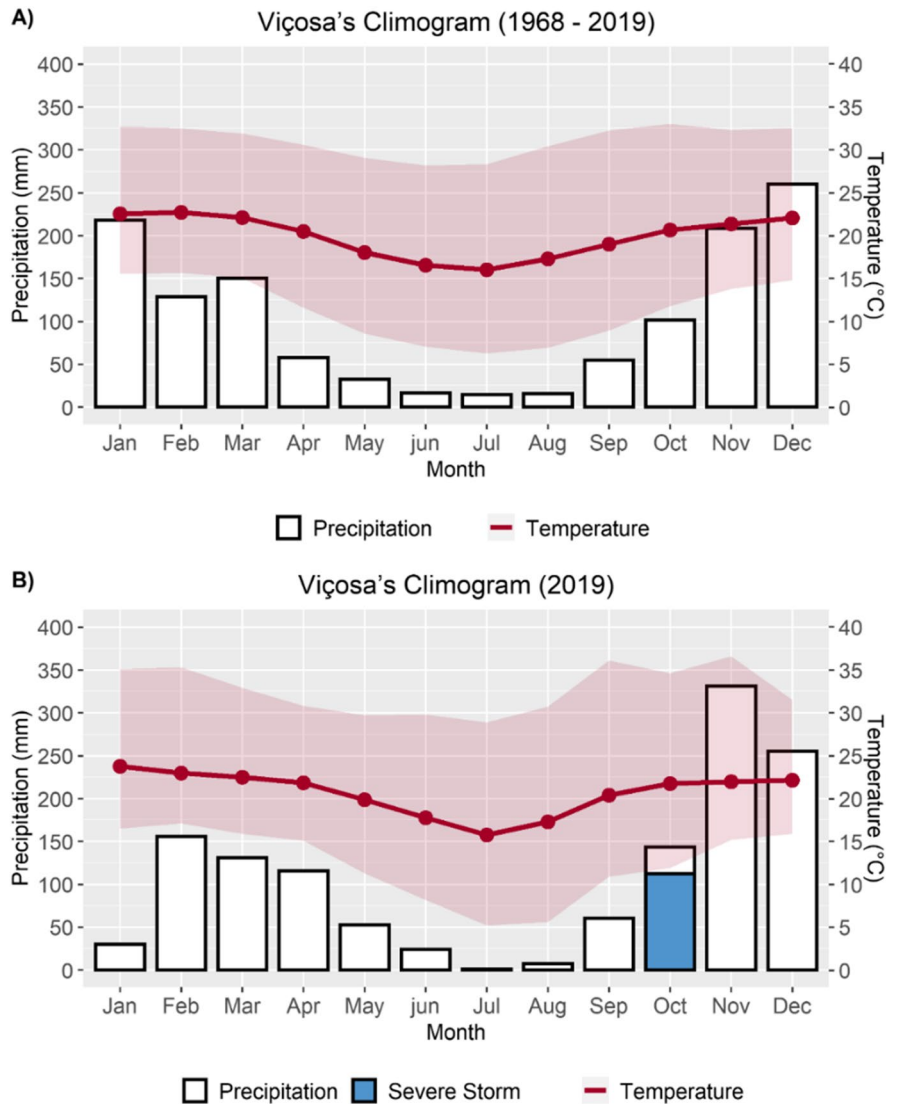

MI). The average values of apparent density and carbon content were extracted from distinct CWD decay classes, as documented by Villanova et al. (2023), within the same forest fragment analyzed in this study (Fig. 4). These values played a key role in the quantification of necromass and carbon stock, respectively.

The CWD volume were calculated using the Smalian's formula (Smalian, 1837), according to the expression $V = (SA_1 + SA_2)/2 \times L$, where V is the volume, in m^3; SA_1 and SA_2 are the sectional areas obtained at the ends of the CWD sections, in m^2; and L is the length of the section, in m. The necromass was quantified by multiplying the volume per the CWD apparent density ($N = V \times \rho_i$, where

N is the necromass, in Mg ha^{-1}; V is the volume, in m^3; and ρ_i is the CWD apparent density of the ith decay class, in g cm^{-3}). The CWD carbon stock were quantified by the product between the necromass and the CWD carbon content, in each decay class ($CS = N_i \times C_i$, where CS is the carbon stock, in MgC ha^{-1}, by decay class; N_i is the necromass, of the i-th decay class, in Mg ha^{-1}; and C_i is the carbon content, of the i-th decay class, in %). The CWD volume, necromass, and carbon stock were quantified before and after the storm. The values obtained after the storm characterize the increment of these parameters as a function of the occurrence of the extreme climatic event.

Fig. 3 Photos taken in the forest fragment after the occurrence of the severe storm, showing **A**) whole trees uprooted; **B**) high density of dead trees; **C**) trees with broken crowns; **D**) formation of gaps in the forest canopy and accumulation of necromass above the forest floor
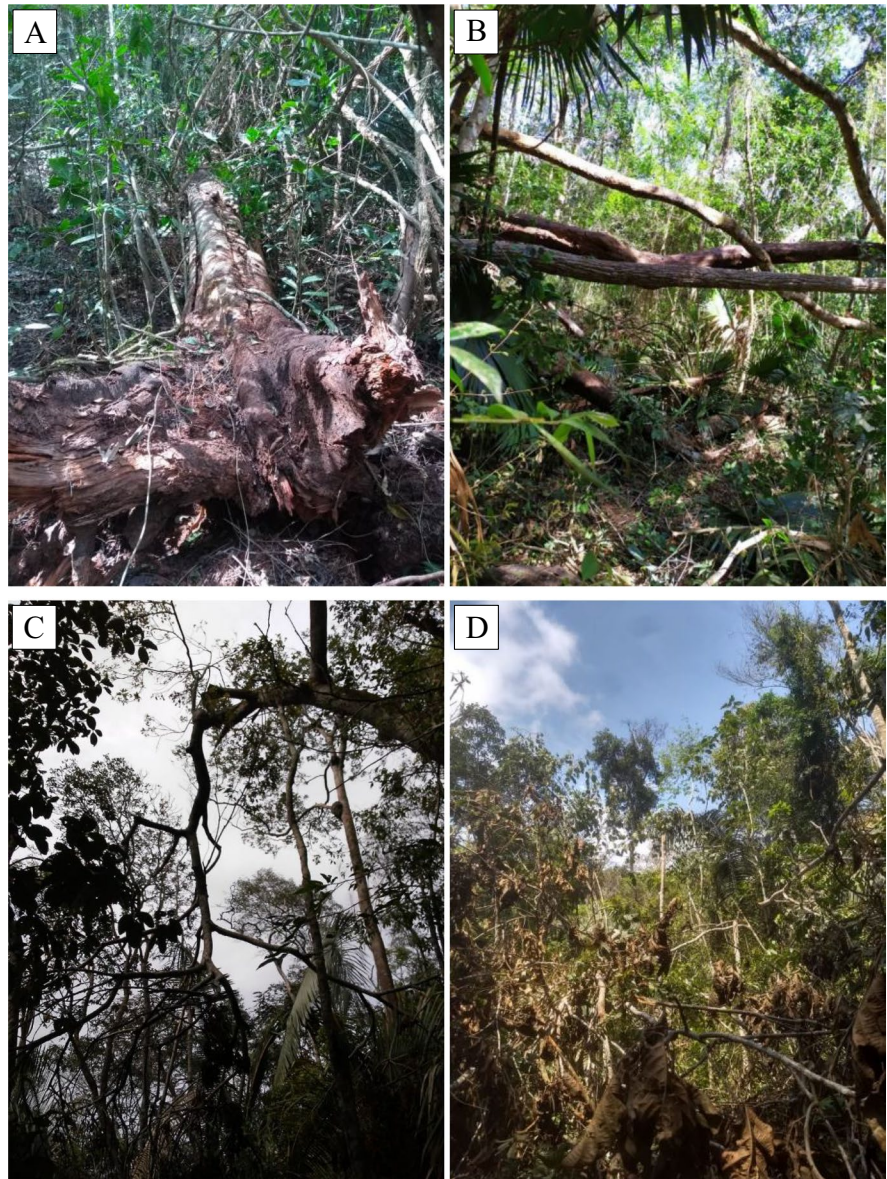
Principal component analysis

Principal component analysis (PCA) (Abdi & Williams, 2010; Hotelling, 1933) was used to indicate the variables that most contributed to the CWD carbon increase in in each plot. Seven variables were used in the PCA, being divided into spatial variables and intrinsic variables to the forest fragment. The spatial variables refer to the terrain topography and express the elevation (m), declivity (%), and slope angle (degrees). These variables were obtained by the *Point Sampling Tool* plugin from QGIS 3.10.6 software

(QGIS.org, 2020), using digital elevation models generated by the Topodata project (INPE, 2011; Valeriano & Rossetti, 2012). The forest intrinsic variables refer to the tree structure and quality. The forest structure was represented by the basal area variable, in m². The quality of the trees was represented by the variables: (i) percentage of trees with lianas; (ii) percentage of trees that had defective trunks; (iii) number of standing dead trees. The basal area and the first two qualitative variables ("i" and "ii") were obtained from the forest inventory of living trees in the year 2016, while the last qualitative variable ("iii") was
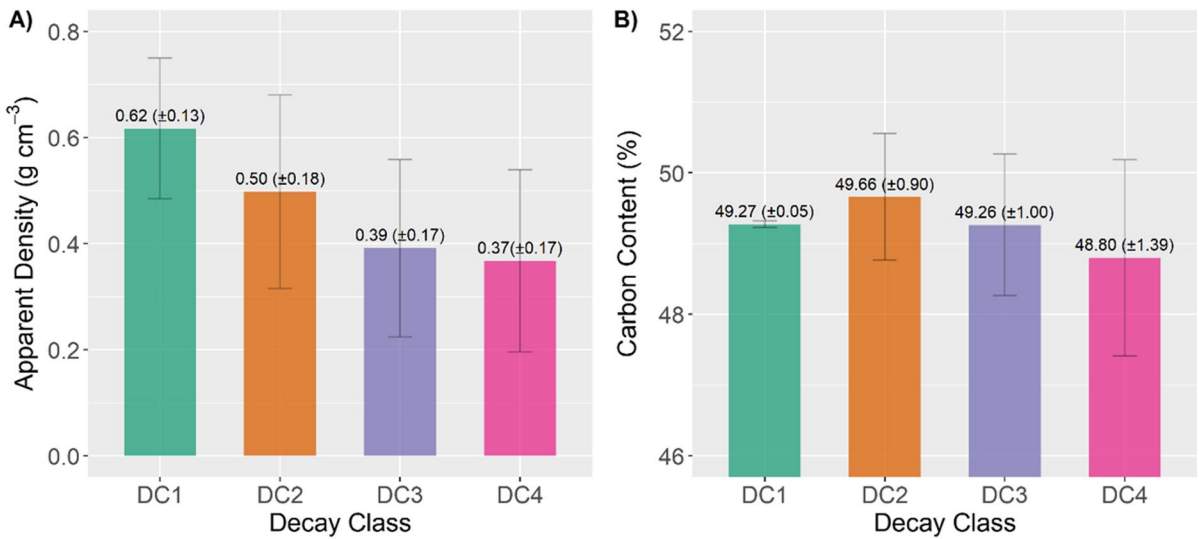
Fig. 4 **A**) Apparent density (g cm^{-3}) and **B**) carbon content (%) for the decay classes of CWD (mean ± standard deviation) obtained by Villanova et al. (2023) and used in this study to quantify necromass and carbon stock, respectively. Decay classes: (DC1) materials recently fallen to the forest floor, with leaves and bark intact; (DC2) materials similar to those in class "DC1," but exhibiting signs of bark decay or peeling; (DC3) materials in an advanced state of decomposition, displaying some resistance to breakage; (DC4) materials that are highly decayed and friable, lacking resistance to breakage

obtained from the necromass inventory in the year of 2018 (Table 2). The data used were standardized to eliminate the effect of the different units (scales) of the variables evaluated. The *Stats* (R Core Team, 2020) and *factoextra* (Kassambara & Mundt, 2020) packages were used to calculate and plot the PCA, respectively.

Results

The CWD volume, necromass, and carbon stock before the storm were 31.57 m^3 ha^{-1}, 16.05 Mg ha^{-1}, and 7.93 MgC ha^{-1}, respectively. The increment of these parameters after storm was 7.15 m^3 ha^{-1} for the volume, 4.07 Mg ha^{-1} for the necromass, and 2.01 MgC ha^{-1} for the carbon stock, reaching a total of 38.72 m^3 ha^{-1}, 20.12 Mg ha^{-1}, and 9.94 MgC ha^{-1}, respectively, after the storm (Fig. 5).

The carbon stock increment was higher in the CWD classes with materials less decomposed and

Table 2 Variables used in principal component analysis per plot. Spatial variables: elevation (m); Slope angle (degrees); and declivity (%). Forest intrinsic variables: basal area (m^2); percentage of trees with lianas incidence—lianas (%); percentage of trees that had defective trunks—defects (%); and number of standing dead trees—snags (*n*)

Plots	Elevation	Slope_Angle	Declivity	Basal_Area	Lianas	Defects	Snags
1	705.48	191.56	21.79	3.52	35.76	39.74	13
2	709.93	154.26	32.75	2.49	21.33	34.00	14
3	718.78	151.15	32.75	2.08	21.32	18.38	12
4	732.49	152.12	32.63	2.02	13.43	63.43	9
5	732.75	205.42	26.10	1.61	13.40	41.24	9
6	739.95	203.65	26.01	2.95	14.88	62.81	6
7	735.30	186.44	26.05	5.13	4.80	26.40	9
8	721.64	162.02	28.41	3.31	2.37	14.20	15
9	729.59	139.91	28.36	3.00	27.54	71.01	6
10	711.06	191.75	12.16	3.26	22.45	28.57	13

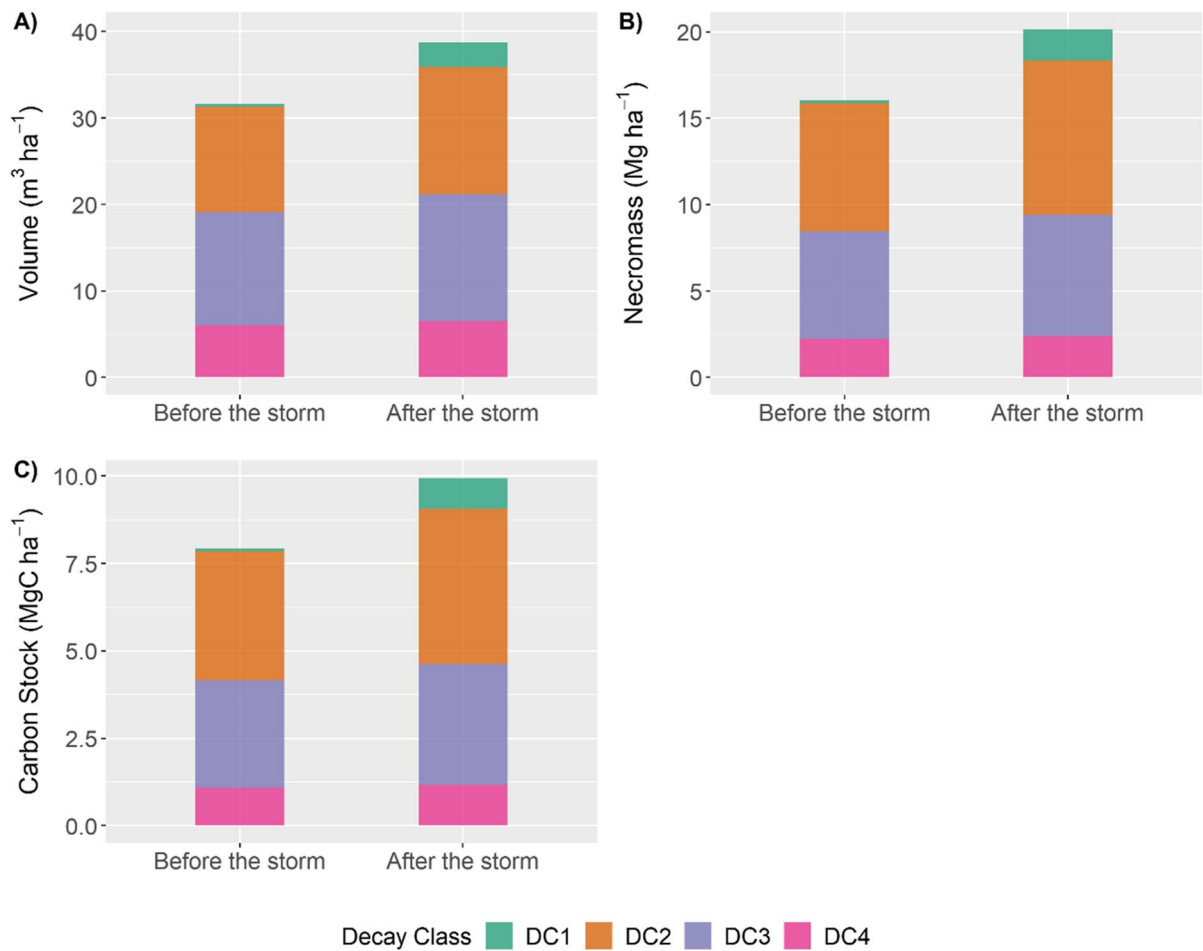**Fig. 5** **A**) Volume (m³ ha⁻¹), **B**) necromass (Mg ha⁻¹), and **C**) carbon stock (MgC ha⁻¹) before and after the storm, by decay class. Decay classes: (DC1) materials recently fallen to the forest floor, with leaves and bark intact; (DC2) materials similar to those in class "DC1," but exhibiting signs of bark decay or peeling; (DC3) materials in an advanced state of decomposition, displaying some resistance to breakage; (DC4) materials that are highly decayed and friable, lacking resistance to breakage

with smaller diameters. Decay classes 1 and 2, together, showed an increase of 1.55 MgC ha⁻¹ (decay class 1 = 0.78 MgC ha⁻¹ and decay class 2 = 0.77 MgC ha⁻¹), representing 77% of the total increment. In contrast, decay classes 3 and 4 showed a low carbon increment when compared to the less decomposed classes, reaching 0.38 MgC ha⁻¹ and 0.08 MgC ha⁻¹, respectively. The CWD with the smallest diameter centers classes (7.5 to 17.5 cm) showed an increase of 1.29 MgC ha⁻¹ (64.34% of the total increment) while the other centers of diameter classes (22.5 to 42.5 cm) had an increase of 0.72 MgC ha⁻¹ (Fig. 6).

The carbon increment of the plots varied from 0.05 to 0.35 MgC. The largest increases were observed in plots 5, 7, 8, and 9. Plot 5 showed an increase of 0.35 MgC, with the largest fraction being found in the CWD larger diameter. In contrast, plot 9 showed an increase of 0.32 MgC, with most of this increase concentrated in CWD smaller diameter. Plots 7 and 8 showed an increment of 0.29 MgC and 0.25 MgC, respectively, with the increment distributed over most of the CWD diameter centers class (Table 3).

The first two main components of PCA explained 61.9% of the total variation in the data (Dim1=36.1% and Dim2=25.8%). The most representative variables
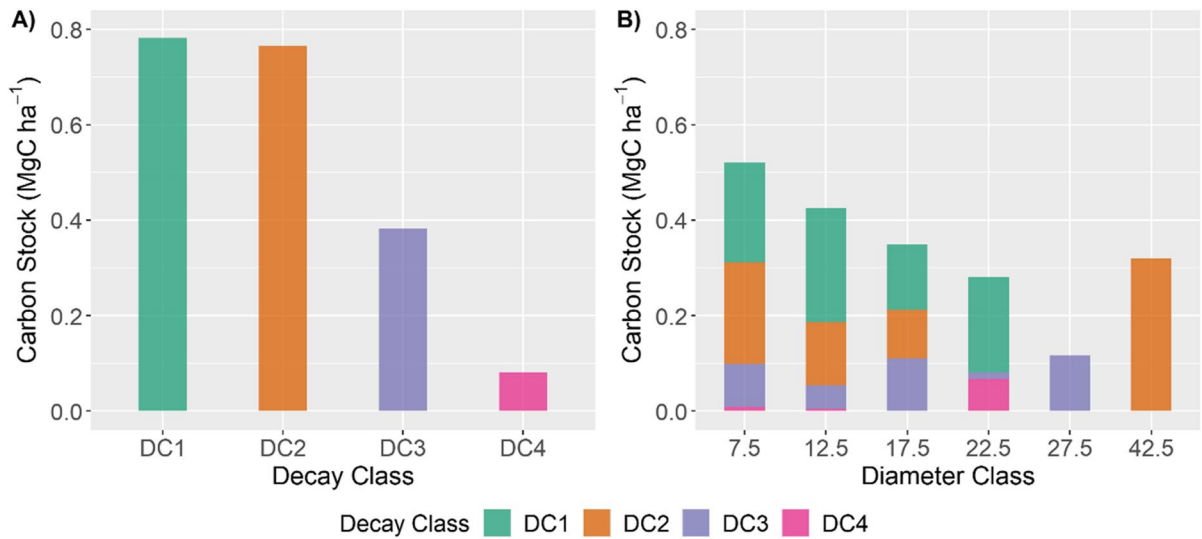
Fig. 6 A) Increase in carbon (MgC ha^{-1}) after the storm, by CWD decay classes; **B**) increase in carbon (MgC ha^{-1}) after the storm, by CWD diameter classes. Decay classes: (DC1) materials recently fallen to the forest floor, with leaves and bark intact; (DC2) materials similar to those in class "DC1," but exhibiting signs of bark decay or peeling; (DC3) materials in an advanced state of decomposition, displaying some resistance to breakage; (DC4) materials that are highly decayed and friable, lacking resistance to breakage

Table 3 CWD carbon increment after the storm, by plot and diameter center class. Plots size: 20 m × 50 m (0.1 ha)

| Plots	Diameter class (cm)						Total
	7.5	12.5	17.5	22.5	27.5	42.5	
1	0.05	0.04	0.08	–	0.07	–	0.24
2	0.05	0.08	0.03	0.03	–	–	0.19
3	0.04	0.03	0.01	–	–	–	0.08
4	0.07	0.03	0.02	–	–	–	0.12
5	0.02	0.01	–	–	–	0.32	0.35
6	0.02	0.03	–	–	–	–	0.05
7	0.06	0.03	0.03	0.08	0.05	–	0.25
8	0.03	0.04	0.05	0.17	–	–	0.29
9	0.13	0.07	0.12	–	–	–	0.32
10	0.06	0.05	0.00	–	–	–	0.11
Total	0.52	0.43	0.35	0.28	0.12	0.32	2.01

of the first component (Dim1) were the number of standing dead trees, elevation of the plots, and the percentage of trees with defective trunks. For the second component (Dim2), the variables slope angle, declivity, and basal area were the most representative. The analysis of the principal components indicated that the percentage of trees with defective trunks and the elevation had greater weight in the carbon increment in plot 5. These variables, added to the declivity, had greater importance in the carbon increase in plot 9. The number of standing dead trees had a great weight in the increment of plot 8, while the basal area and slope angle were the variables that most impacted the increment in carbon of plot 7 (Fig. 7).
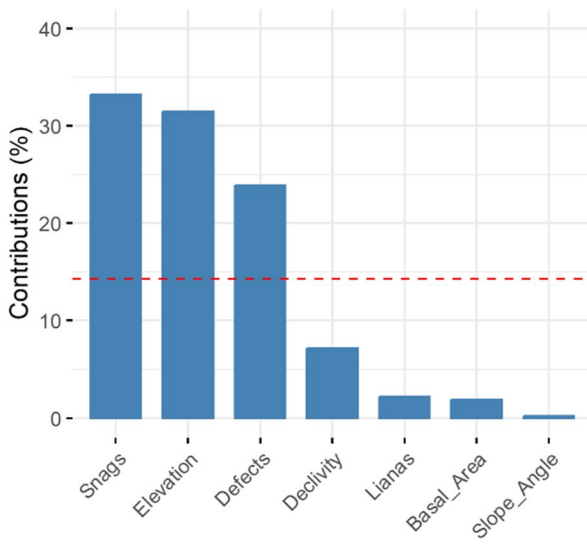
Discussion

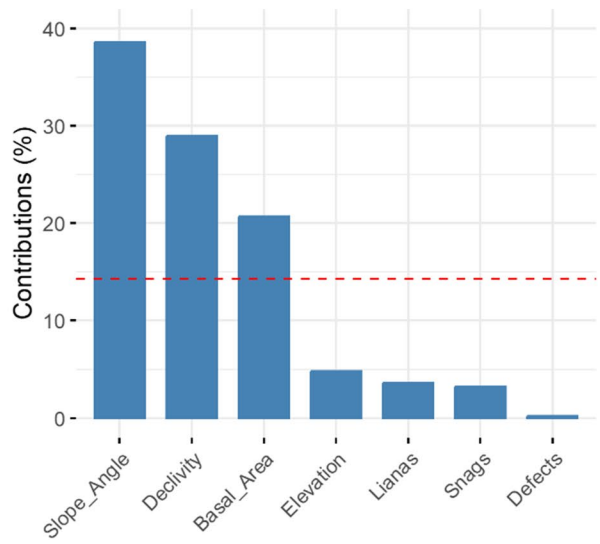Severe storms modify the structure of the tropical forest and impact growth dynamics (Chambers et al.,

A) PCA - Biplot
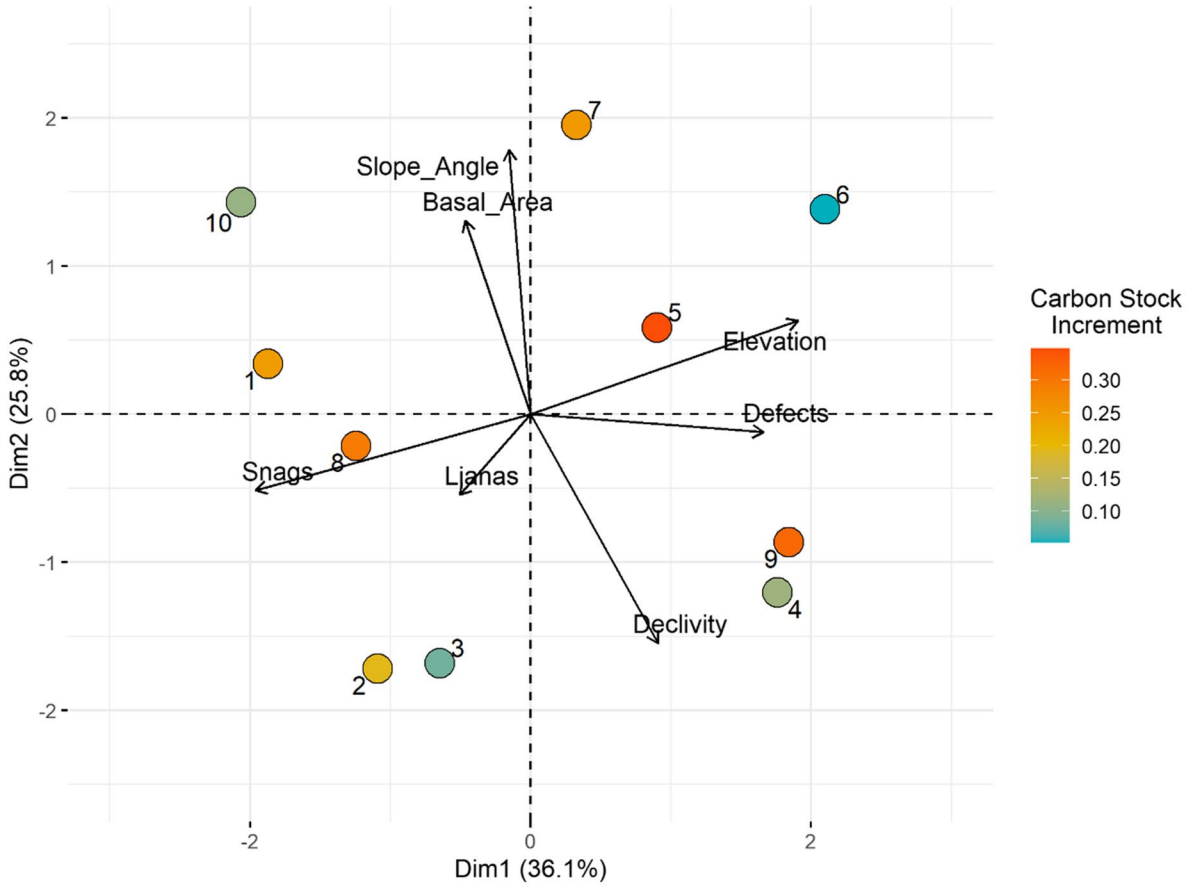
B) Contribution of variables to Dim-1

C) Contribution of variables to Dim-2

◄**Fig. 7 A**) Biplot generated by the analysis of the main components (PCA) of spatial and intrinsic variables to the forest fragment; **B**) contribution of variables to the first component of the PCA (Dim1); **C**) contribution of variables to the second component of the PCA (Dim2). The points on the Biplot represent the plots and the colors represent the increase in carbon due to the occurrence of the storm. The black arrows are the variables used to build the PCA. Variables used: percentage of trees with defective trunks (*Defects*); number of standing dead trees (*Snags*); elevation (*Elevation*); slope angle (*Slope_Angle*); declivity (*Declivity*); basal area (*Basal_Area*) and the percentage of trees with lianas (*Lianas*)

2013; Chao et al., 2022; Schwartz et al., 2017; Silvério et al., 2019; Trumbore et al., 2015), causing sudden losses of living biomass (Negrón-Juárez et al., 2010) and altering forest carbon stocks and fluxes (Espírito-Santo et al., 2014a, b; Vanderwel et al., 2013). However, the effects of these storms on the CWD carbon increment are still poorly understood, especially in the Atlantic Forest. This study attempted to elucidate this scientific gap by conducting CWD forest inventories both before and after a severe storm. Through this approach, we aim to improve our understanding of the factors that influence the estimates of this parameter, contributing to a more comprehensive view of the process.

The CWD volume, necromass, and carbon stock exhibited a significant increase due to the occurrence of a severe storm (Fig. 5). The carbon increase reached 2.01 MgC ha^{-1}, representing about 25% of the carbon stock already existing in the forest before the storm. This increase was concentrated in the CWD less decomposed (decay classes 1 and 2) and with smaller diameter centers classes (7.5 to 17.5 cm), indicating that small and healthy trees had high mortality during the extreme climatic event (Fig. 6). The trees' mortality with these characteristics occurs mainly due to the fall of trunks or branches with high diameters that, when falling on the forest floor, can kill or damage neighboring trees. In addition, the decrease in tree density can still indirectly affect the survival probability of the remaining trees due to their increased exposure to the storm (Canham et al., 2001; Rifai et al., 2016; Vanderwel et al., 2013).

The carbon increase showed great variation between the inventoried plots after the extreme climatic event (Table 3). These differences can be explained by the trunk and branch falls with different diameters (Rifai et al., 2016) and by spatial, structural, and qualitative factors intrinsic to each plot (de

Toledo et al., 2013; Schwartz et al., 2017). The impact of these factors on the plots carbon increment, mainly in the ones with highest increments (plots 5, 7, 8, and 9), was elucidated through the PCA (Fig. 7). The PCA indicated that the percentage of trees with defective trunks and the elevation had major importance in the carbon increment of plot 5. In fact, defective trees with hollow trunks or that show apparent cracks or rot are more likely to be broken during a storm (Heineman et al., 2015; McDowell et al., 2018). In addition, areas at higher altitudes and close to hilltops are subject to greater exposure to wind, characterized by higher speeds, which may cause greater breakage or uprooting of trees (Marra et al., 2014; Ruel et al., 2001). Elevation can also affect the plots' floristic composition (Brown et al., 2013; Jucker et al., 2018; Toledo et al., 2017), with species of varying physical strengths. The fast-growing species (pioneers), for example, have lower wood density and, consequently, are more fragile when compared to species from other ecological groups, being broken more easily (Ribeiro et al., 2016; Rifai et al., 2016; Silvério et al., 2019).

The variables Defect and Elevation, added to Declivity, had great weight in the plot 9 carbon increase. Trees located in more sloping areas show changes in the center of gravity of the crowns and constantly suffer from soil creep and landslides, which can be enhanced by the intensity of rainfall during the storm, contributing to an elevated rate of tree mortality (de Toledo et al., 2011; Gale & Hall, 2001; Sasaki et al., 2000; Young & Perkocha, 1994). However, additional research into the anchorage of trees to the ground and their resistance to uprooting needs to be carried out in the study area to determine potential variations between flat and sloped terrain (Nicoll et al., 2005; Ribeiro et al., 2016; Yan et al., 2016). The standing number of dead trees was the most important variable to explain the plot 8 carbon increment. Trees in this condition present great physical fragility because they have already been subjected to some type of stress (competition, suppression, water deficit, flooding, senescence, lightning, or pathogen attack), making the Snags a great carbon source to the forest floor through the winds' action (Chao et al., 2009; de Toledo et al., 2013). The slope angle and the basal area were the variables that had the greatest weight for plot 7 carbon increase. In fact, topographic variables, such as slope angle, and variables that express forest structure, such as basal area, are

positively correlated with the amount of wind damage in a stand, affecting the carbon increment of the plots (McGroddy et al., 2013; Negrón-Juárez et al., 2014; Schwartz et al., 2017; Xi et al., 2008).

Severe storms, like the one observed in this study, are anticipated to increase in frequency and intensity as a result of climate change (Knutson et al., 2010; Negrón-Juárez et al., 2010; Taccoen et al., 2021). This escalation is projected to lead to heightened tree mortality and a substantial accumulation of carbon in CWD within forest ecosystems. Consequently, understanding the susceptibility of forests to the intense rains action and strong winds becomes fundamental to model and monitor the future impacts of these extreme climatic events in the Atlantic Forest fragments.

Conclusions

Severe storms events induce substantial increments in coarse woody debris (CWD) carbon stocks within fragments of the Atlantic Forest. This surge is notably shaped by heightened mortality rates among smaller, previously healthy trees. Tree mortality and the consequent CWD carbon accumulation occurs non-randomly in the forest fragment, being influenced by spatial (elevation, slope angle, and declivity), structural (basal area), and qualitative factors (trunk quality and tree health) intrinsic to the forest. This research underscores the significance of comprehending these complex connections to advance our broader understanding of forest carbon dynamics and their implications for ecosystem management and climate change mitigation strategies.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical responsibilities of authors All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

Competing interests The authors declare no competing interests.

Ethics approval The collection of plant material, experimental research, and field studies complied with relevant institutional, national, and international guidelines and legislation.

Consent to participate Not applicable.

Consent for publication Not applicable.

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