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Scientific Article

LONG-TERM ASSESSMENT OF FIRE-INDUCED CARBON LOSS IN SOUTHEAST ATLANTIC FOREST

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ABSTRACT

Fires threaten tropical forests such as Atlantic Forest in Brazil, compromising the ecosystem service of carbon stock. However, there is a literature gap regarding these studies in these ecosystems. Therefore, we conducted this analysis in different land use and land cover (LULC) classes, considering seasonality and topographic, hydrological, anthropogenic and fire variables correlations, during 2000-2020. The InVEST Carbon model was used, applied to carbon biomass pre-fire and pos-fire, based on field work and linear regression, weighted by pre- and post-fire NBR spectral index. The results, in 21 years, revealed a total loss after fire of 55.7GgC (43%), and of these, 79% is in old-growth Ombrophilous dense. In general, fire negatively impacts the carbon stock of native forests by an average of 38% (ranging from 19.9% to 69.1%, depending on phytophysiognomy and seasonality), Eucalyptus plantations by 87.1%, high-altitude grasslands by 79.5% and pasture in 90.4%. Burn frequency and severity as well as distance from rivers and roads were significantly correlated with carbon loss. A small portion of this biome has shown a high potential for fire-induced carbon loss, indicating a danger for the whole Atlantic Forest conservation and to international agreements commitments.

Keywords: Carbon stock; Ecosystem; InVEST; Fire

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AVALIAÇÃO DE LONGO PRAZO DA PERDA DE CARBONO INDUZIDA PELO FOGO NA MATA ATLÂNTICA DO SUDESTE

RESUMO – Os incêndios ameaçam florestas tropicais como a Mata Atlântica no Brasil, comprometendo o serviço ecossistêmico de estoque de carbono. No entanto, há uma lacuna na literatura em relação a estes estudos nesses ecossistemas. Portanto, realizamos esta análise em diferentes classes de uso e cobertra da terra (LULC), considerando sazonalidade e correlações de variáveis topográficas, hidrológicas, antropogênicas e de incêndios, de 2000 a 2020. Foi utilizado o modelo de Carbono InVEST, aplicado à biomassa de carbono acima do solo pré e pós-incêndio, com base em trabalho de campo e regressão linear, ponderada pelos índices espectrais NBR pré e pós-incêndio. Os resultados, em 21 anos, revelaram uma perda total após incêndios de 55,7GgC (43%), e destes, 79% estão na Foresta Ombrófila Densa em estágio avançado. Em geral, o fogo impacta negativamente o estoque de carbono das florestas nativas, em média 38% (variando de 19,9% a 69,1%, dependendo da fitofisionomia e sazonalidade), de plantios de eucalipto em 87,1%, de campos de altitude em 79,5% e de pastagens em 90,4%. A frequência e severidade dos incêndios, assim como a distância de rios e estradas, estão significativamente correlacionadas com a perda de carbono. Uma pequena porção deste bioma mostrou um alto potencial de perda de carbono induzida pelo fogo, indicando um perigo para toda a conservação da Mata Atlântica e para os compromissos de acordos internacionais.

Palavras-Chave: Estoque de carbono; Ecossistema; InVEST; Incêndio

1. INTRODUCTION

Carbon stock and sequestration are among the most significant ecosystem services due to their role in regulating global climate (Costanza et al., 2017; MEA, 2005; Van der Ploeg et al., 2010; Sannigrahi et al., 2018). Anthropogenic activities have led to an increase of greenhouse gases in the atmosphere on a scale incompatible with the regenerative dynamics of natural carbon cycle, causing disruptions in functioning of the Earth system (UNDRR, 2019) culminating in international agreements (UN, 2015) to limit carbon concentrations (IPCC, 2019). Therefore, is crucial to reduce losses in carbon from deforestation and environmental degradation (Munang et al., 2013), increase ecological restoration (IPCC, 2014), and recognize that adapting to climate change is associated with maintaining associated ecosystem services (O'Brien et al., 2008).

The Atlantic Forest (AF) biome, a biodiversity hotspot (Myers et al., 2000), is home to most of the Brazilian population and the largest cities, with only 12.5% remaining from its original territory, with a history of deforestation followed by fire (Dean, 2004). Although deforestation has decreased (SOS Mata Atlântica & INPE, 2021) the biome is still losing forest cover (Rosa et al., 2021; Souza et al., 2018). This deforestation is partly associated to fire (Baião et al., 2023), whose burning probability increases with small patches of forest adjacent to pastures (Guedes et al., 2020).

However, the evergreen forests in AF biome are fire-sensitive ecosystems (Hardesty et al., 2005), with species that did not evolve under fire regimes (Pivello et al., 2021), and the number of burned areas has been increasing (MapBiomas, 2022). Fire promotes natural system disruption, threatening size, structure and composition of ecosystems (Brando et al., 2014; Carvalho et al., 2022; Sansevero et al., 2020), making it more susceptible to the incidence of forest fires (Pütz et al., 2011), threatening biodiversity and ecosystem services (Kelly et al., 2020; Loiselle et al., 2020; Robinne et al., 2020; Roces-Díaz et al., 2022; Rodrigues et al., 2019; Taboada et al., 2021). Furthermore, carbon losses contribute to climate change (IPCC, 2023, 2019) and several associated disasters (Anderson and Cunningham, 2019; Campanharo et al., 2019).

Carbon stock (CS) can be estimated by the amount of carbon biomass measured in field works (Ferez et al., 2015; Vieira et al., 2011) or modeling (Natural Capital Project, 2023). Although there is literature on post-fire carbon biomass, especially in the Amazon Forest (Anderson et al., 2015; Barbosa and Fearnside, 1999; Barlow et al., 2003; Cochrane and Laurance, 2002; Pessôa et al., 2020; Vasconcelos et al., 2013), the literature on post-fire carbon in the Atlantic Forest it is incipient. Likewise, few studies estimated the carbon loss (Garrastazú et al., 2015; de Lima et al., 2020; Pavani et al., 2018), but none of them has investigated fire as a conditioner. Recently, a study showed that the widely accepted drivers of CS, such as climate, soil, topography, and forest fragmentation, have a much smaller role than the forest disturbance history of the AF (Pyles et al., 2022). Thus, investigating the fire threat on CS of the AF across different land uses is imperative.

Our hypothesis is that the native forest is was more impacted by fire and loses more carbon than areas with less biomass, and that slope, drought and burn severity are the variables associated with fire, that influenced most the carbon loss. We also hypothesize that seasonality interferes with fire-induced carbon loss. Therefore, this study aimed to estimate carbon loss induced by fire in a Southeast Atlantic Forest protected area, considering land use and land cover (LULC), from 2000 to 2020, as well as to investigate the influence of different variables.

2. MATERIAL AND METHODS

2.1 Study area

The study area is situated in the southeast Atlantic Forest biome, specifically within the Paraíba do Sul River Basin. This region has undergone various economic cycles leading to fragmentation and deforestation (Devide et al., 2014), reducing forest to 32.8% (MapBiomas Project, 2023). The basin provides water resources for over 15.7 million inhabitants but faces an increasing trend of fires, some of which are linked to deforestation (Baião et al., 2023). APA Silveiras (Environmental Protection Area), chosen as the study area (Figure 1), experiences a high number of fire incidents, particularly in forested areas (Souza

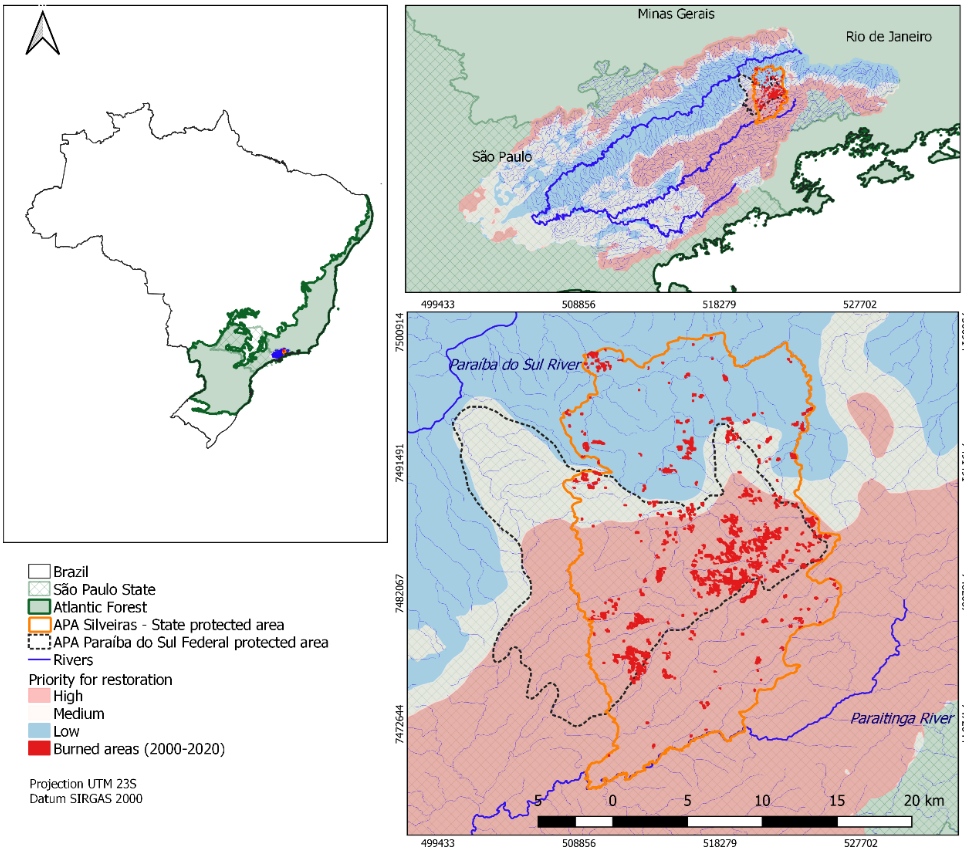

Figure 1. Study area in Atlantic Forest biome, APA Silveiras, São Paulo State, Paraíba do Sul River Valley, overlapped by APA Paraiba do Sul and burned areas from 2000 to 2020 > 1ha

Figura 1. Área de estudo no Bioma Mata Atlântica, APA Silveiras, Estado de São Paulo, Vale do Rio Paraíba do Sul, sobreposta pela APA federal Paraíba do Sul e áreas queimadas de 2000 a 2020 > 1ha

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et al., 2020). APAs are a type of protected area (PA) in Brazil, classified as a sustainable use are (Brasil, 2000).

The APA Silveiras has an area of 414.782 km2, with hilly and mountains that reach 1,902 m (ASF DAAC, 2023), and presents a humid subtropical climate (Alvares et al., 2014). It has 59% of its area defined as high priority for restoration and conservation (São Paulo & Fundação Florestal, 2018), comprising headwater areas and an area of the APA Paraíba do Sul . LULC is 37.1% of forest formation, 36.67% of pasture, 19.35% of mosaic, 4.94% of forestry (eucalyptus) and the remainder occupied by rocky outcrops, agriculture and non-vegetated areas (Souza et al., 2020). Native vegetation is distributed in Ombrophilous Dense Forest (ODF, 84%), high-altitude grasslands (HAG, 10%), semideciduous seasonal forest (SSF, 5%) and mixed Ombrophilous forest (OMF, 1%) (São Paulo, 2020).

2.2 Dataset

Burned areas were obtained from datasets of MapBiomas Project, an Annual Mapping of Land Use and Coverage project in Brazil composed of a multidisciplinary network that uses cloud processing and pattern recognition methodologies to generate a historical series of annual maps of LULC in Brazil, from images of Landsat satellites, with 30 m resolution (https://mapbiomas.org/). For this work, we use monthly accumulated and annual frequency fire scars (Alencar et al., 2022) and LULC (Souza et al., 2020).

Normalized Burned Ratio (NBR) is an index indicated for studying vegetation quality and therefore, bi temporal difference of NBR is used in detection and investigation of burn severity (Garcia and Caselles, 1991;Key and Benson, 2006) and it uses the near infrared (NIR) range where there is high reflectance from vegetation, and the shortwave infrared (SWIR) range where there is low reflectance from vegetation and high reflectance from soil (Jensen, 2009). In the same way, we also used Normalized difference vegetation index (NDVI) with NIR and red (R) bands. We calculated NBR and NDVI (for each month and year of time series) from collections of atmospherically corrected surface reflectance images available on Google Earth Engine (GEE) platform (https://developers.google.com/earth-engine/datasets/catalog/landsat), courtesy of U.S. Geological Survey, using Landsat images (Equation 1 and Equation 2).

$$NBR = (NIR - SWIR2)/(NIR + SWIR2) \quad \text{(Eq. 1)}$$

$$NDVI = (NIR - R)/(NIR + R) \quad \text{(Eq. 2)}$$

From DataGeo system (https://datageo.ambiente.sp.gov.br/), Forest Inventory (São Paulo, 2020) we had forest phytophysiognomies and Priority Areas for Restoration and Conservation in Paraíba do Sul River basin (São Paulo, 2018), as same as drainage map from São Paulo Hydrography. A road map with high resolution, including non-pavement roads, was obtained from Open Street Map (https://download.geofabrik). For topography survey, the digital elevation model (DEM) was obtained from ALOS PALSAR Radiometric terrain High resolution data, 12,5 m (ASF DAAC, 2023), from where we obtained slope and global solar radiation.

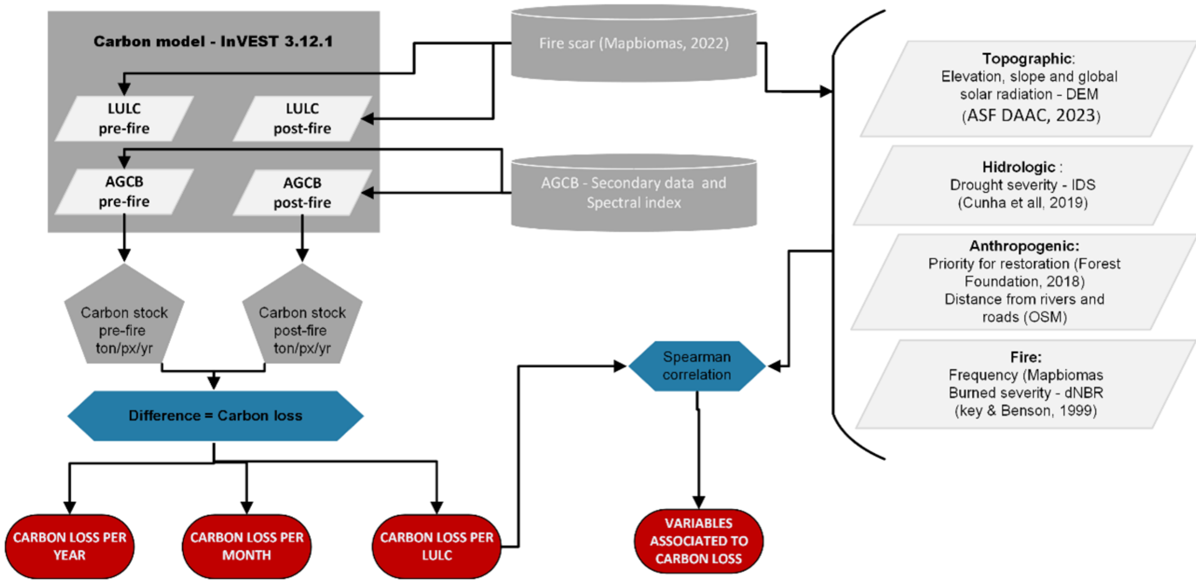
The Integrated Drought Index (IDI), which consists of combining Standardized Precipitation Index (SPI), with Vegetation Health Index (VHI), from do Amaral Cunha et al. (2019). While SPI quantifies abnormal wetness and dryness, VHI captures spatial details and reflects vegetation or soil water stress. Together, these indices provide complementary insights into drought conditions, representing both precipitation deficits and surface responses to soil water shortages (Marengo et al. 2020). The gis-software used for analyses was Quantum Gis 3.16.11.

2.3 Data Analysis

Data were analyzed and processed following methodological procedures described in Figure 2. Methodological steps are described in the next sections.

2.4 Burned area selection

Using GEE, we vectorized LULC and fire scar data, for further processing in Quantum



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Gis. To reduce the computational cost, we assumed to select a scar ≥1 ha of 6,147 burned areas found in APA Silveiras, occurring in forest, high-altitudes grasslands, pasture and eucalyptus areas. Then, we superimposed on the Forest Inventory (São Paulo, 2020) to identify phytophysiognomy. Thus, we filter 542 burned areas, being 294 pasture (3.75 ha ±4.28), 4 forestry (3.45 ha ±2.59), 178 old-growth forest (142 Ombrophilous dense – ODF (6.51 ha ±13.47), 5 semideciduous – SSF (2.17 ha ±1.35), 10 mixed Ombrophilous – OMF (7.11 ha ±6.32)), 21 high-altitude grasslands – HAG (4.68 ha ±5.59)) and 66 secondary forest (55 ODF (2.47 ha ±1.56), 8 SSF(2.49 ha ±1.97) and 3 OMF (2.31 ha ±0.97)). These areas were also classified by year and month of occurrence. We then produce a new LULC map for each year of the time series including burned areas, as explained in next section.

2.5 Estimating fire-induced carbon loss

In the absence of post-fire biomass data in the AF, we adapted equations from previous studies (Anderson et al., 2015; Pessôa et al., 2020) to estimate aboveground carbon biomass (AGCB) in burned areas. These equations were developed based on field measurements of biomass in both burned and unburned areas in the Amazon and Cerrado regions, focusing on studies conducted within one year after fires. We included data from pastures and grasslands while excluding values exceeding the maximum AGCB observed in the Atlantic Forest. Additionally, we categorized pre-burn biomass data into two groups: below and above 40 tons per hectare. Subsequently, we developed separate regression equations for areas with low and high biomass. These equations were then applied to AGCB estimates from various studies conducted in the AF and related areas, such as Cerrado grasslands. For studies estimating total aboveground biomass, we assumed 50% to carbon biomass, following established literature (Anderson et al., 2015; Ditt et al., 2010; Metzker et al., 2011; Pessôa et al., 2020). We calculated the average, minimum, and maximum pre-fire and post-fire AGCB values for each land use and land cover (LULC) class.

To account for seasonality, we incorporated the median values of the NBR and NDVI of burned areas into the AGCB ranges for respective LULC types. Given that NBR demonstrated better alignment with average AGBC data, we opted to prioritize its use in our analysis.

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$$AGCB_{w_{pre}} = Min_{un} + (Max_{un} - Min_{un}) * NBR_{pre} \text{ (Eq. 3)}$$

$$AGCB_{w_{post}} = Min_{b} + (Max_{b} - Min_{b}) * NBR_{post} \text{ (Eq. 4)}$$

where AGCBw is the aboveground carbon biomass pre and post fire weighted, Min and max are the minimum and maximum AGCB values of unburned areas (literature - un), and burned areas (adjusted Equation - b). NBR is the median for month/year, considering Landsat interval (~15 days).

In the secondary forest, we estimated the AGCB by multiplying old-growth forest values by the average values (0.52) from other works related to the AF (Bieluczyk et al., 2023; Brasil, 2016; Ditt et al., 2010; Lemos et al., 2023; Metzker et al., 2011).

We used the InVEST 3.12.1 (Integrated Valuation of Ecosystem Services and Tradeoffs (Natural Capital Project, 2023)) Carbon model, according literature (Babbar et al., 2021; Fernandes et al., 2020; Garrastazú et al., 2015; Hu et al., 2020; Pavani et al., 2018). The model operates with input data from LULC maps and the amount of carbon stored in carbon pools, as aboveground, generating estimates of the amount of carbon stored in a share of land over time (Natural Capital Project, 2023). Using a raster map, the model assigns a LULC class to each cell and estimates the amount of carbon for each class using a lookup table, producing a map of CS in the landscape (Pavani et al., 2018).

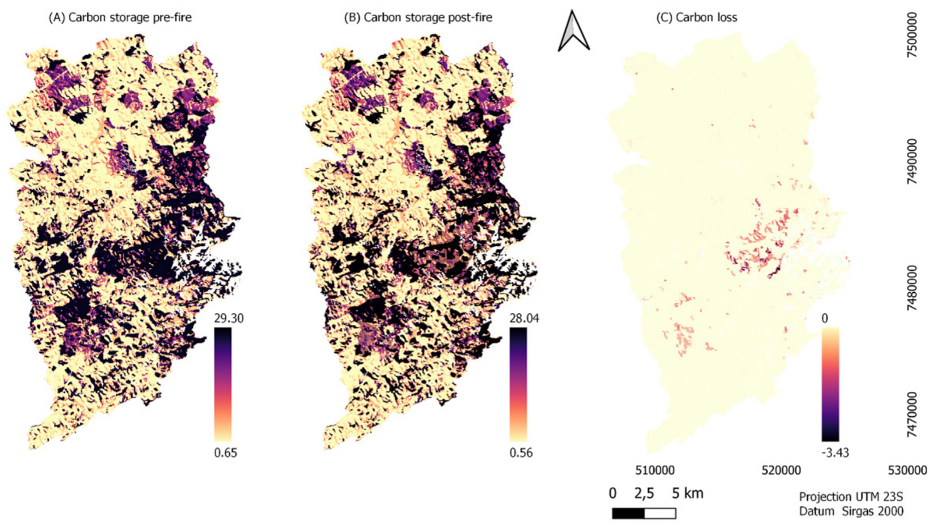
In this study, we produce pre and post-fire lookup tables by year, using AGCBwpre and AGCBwpost, respectively, with ran model twice a year. Unburned areas, we attributed the same AGCB value in pre and post fire.

Then, we subtracted the pre from post raster by year, allowing us to estimate the carbon loss. We also analyzed significant differences between LULC classes averages in carbon loss using post hoc Tukey test in Python with Scipy libraries (Virtanen et al., 2020).

Finally, we analyzed the relantionship between topography, hidrologic, anthropogenic and fire variables and carbon loss per LULC class, by Spearman correlation in Python 3.6 with Scipy libraries (Virtanen et al., 2020).

3. RESULTS

In our analysis of 2385.18 ha of burned areas, total fire-induced carbon loss was 55.71 Gg C, corresponding to 43.3% of the pre-fire AGCB, with relative stock of 53.9 MgC/ha and carbon loss of 23.35 MgC/ha. Among the total carbon loss, old-growth ODF predominated (79%), ranking second burned fragments after pastures. These occurrences were primarily concentrated in APA Silveiras central region (Figure 3A, Figure 3B and Figure 3C). The years 2000, 2003, 2014 and 2020 exhibited the highest carbon losses (Figure 3D), while September and October recorded greatest



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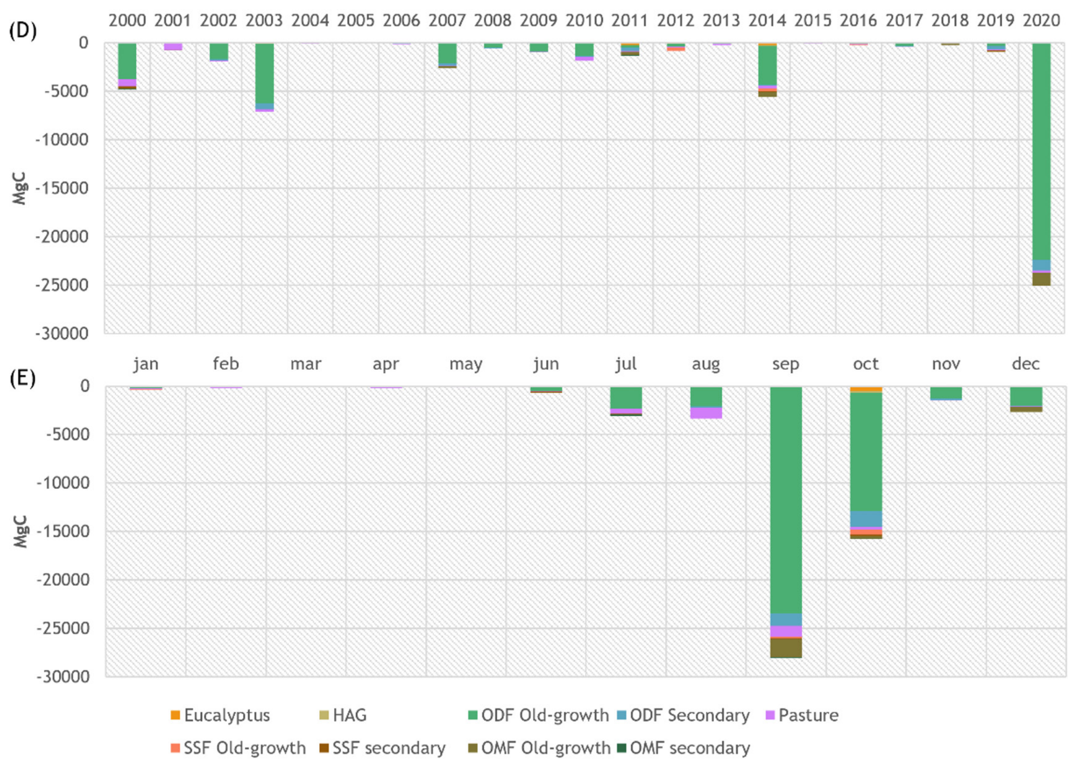


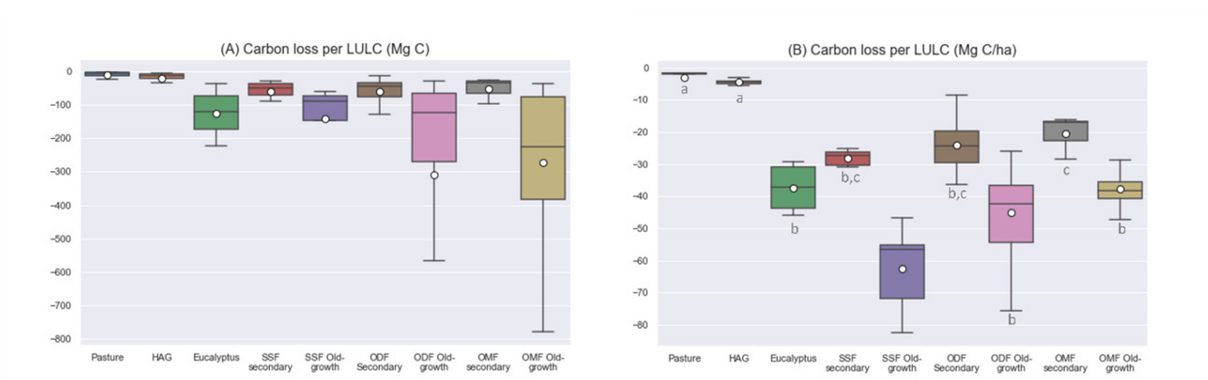
Figure 3. Carbon storage before fire (A), after fire (B) and balance (C) in time series from 2000 to 2020 (D) and fire months (E) in APA Silveiras, Southeast Atlantic Forest, Brazil

Figura 3. Estoque de carbono antes do fogo (A), depois do fogo (B) e saldo (C) na série temporal de 2000 ta 2020 (D) e meses de fogo (E) na APA Silveiras, Mata Atlântica do Sudeste, Brasil

losses across years (Figure 3E).

Old-growth forests, followed by secondary forests and eucalyptus, exhibited more substantial carbon losses compared to other land cover classes, with significant disparities observed between low and high biomass classes (Figures 4A and Figure 4B). While carbon losses fluctuated across years and months (Figure 4C and Figure 4E), no significant differences were noted, except for 2014 and August compared to October, November, and December (Figure 4D and Figure 4F).

In general, low Spearman correlation was observed. Elevation and restoration priority negatively linked to carbon loss with high correlation in eucalyptus (Figure 5). Burn frequency has a low positive correlation in



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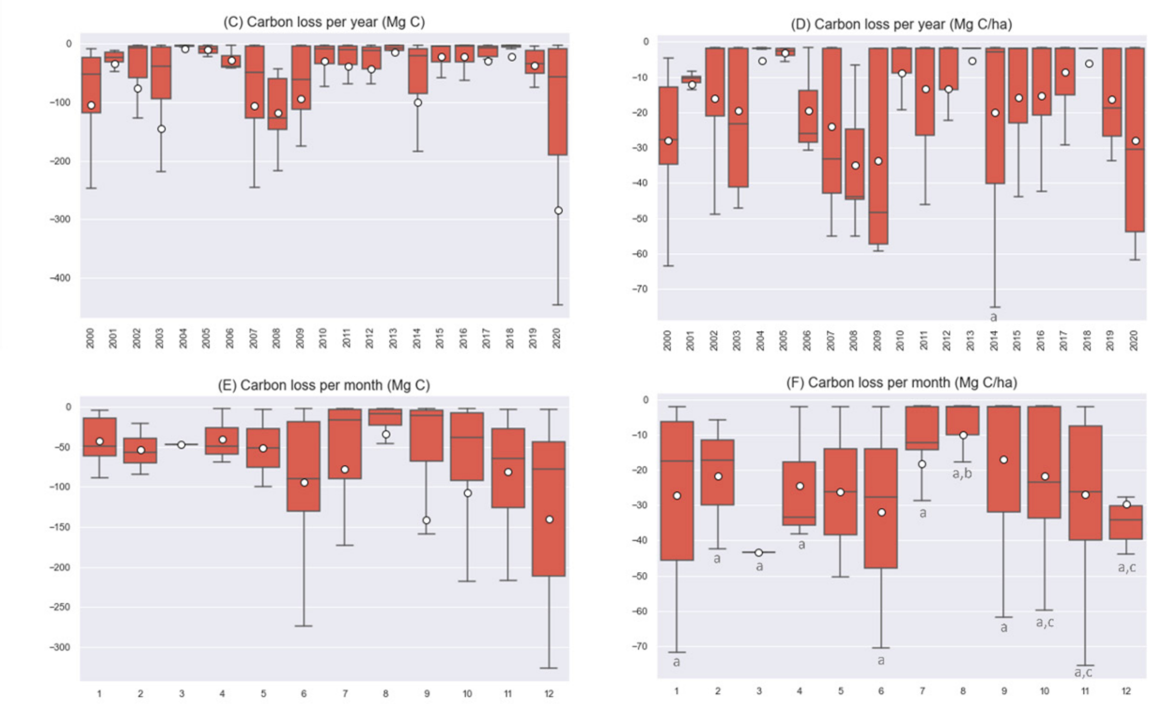

Figure 4. Boxplot of carbon loss per LULC (A-B), year (C-D) and month (E) and (F) from 2000 to 2020 (left – total carbon loss and right – carbon loss per hectare) in APA Silveiras, Southeast Atlantic Forest, Brazil

Figura 4. Boxplot da Perda de carbono por LULC (A-B), ano (C-D) e mês (E-F) de 2000 a 2020 (esquerda – Perda total de carbono, e direita – perda de carbono por hectare) na APA Silveiras, Mata Atlântica Sudeste, Brasil

Carbon loss	Radiation	Elevation	Slope	Drought	Frequency	Severity	Rivers	Roads	Priority
General	0,8	**-1,0**	-0,4	0,9	-0,8	0,4	-0,4	-0,4	**-0,2**
ODF Old-growth	0,1	0,1	-0,1	0,1	**0,3**	**0,3**	**-0,4**	**-0,2**	-0,3
ODF Secundary	-0,1	0,1	0,1	0,1	0,1	**0,4**	-0,4	-0,3	-0,2
OMF Old-growth	-0,3	0,2	0,0	0,5	0,7	**0,6**	-0,3	-0,6	—
OMF Secondary	0,5	-0,5	-0,5	-0,9	0,0	0,5	**1,0**	-0,9	—
SSF Old-growth	0,3	0,3	-0,1	-0,6	—	0,5	-0,5	0,5	-0,4
SSF Secondary	0,5	0,0	0,0	-0,3	—	-0,1	-0,4	0,0	-0,6
HAG	-0,3	0,1	0,2	0,1	0,2	0,3	0,0	0,0	—
Pasture	0,1	**-0,2**	0,0	0,0	-0,1	0,0	-0,2	-0,1	-0,2
Eucalyptus	0,8	**-1,0**	-0,4	0,9	-0,8	0,4	-0,4	-0,4	**-0,8**

1,0 0,8 0,5 0,25 0 -0,3 -0,5 -0,8 -1,0

Figure 5. Spearman correlation between carbon storage and variables in burned LULC class (black bold p<0,05) in APA Silveiras, Southeast Atlantic Forest, Brazil (ODF = Ombrophilous dense forest; SSF = Semideciduous Forest; OMF = Mixed Ombrophilous forest; HAG = High-altitude fields)

Figura 5. Correlação de Spearman entre estoque de carbono e variáveis nas classes de LULC queimadas (negrito p<0,05) na APA Silveiras, Mata Atlântica Sudeste, Brasil (ODF = Floresta Ombrófila Densa; SSF = Floresta Semidecídua; OMF = Floresta Ombrófila Mista; HAG = Campos de altitude) old-growth ODF as well as burn severity in both secondary and old-growth ODF and distance to rivers and roads (negatively) in ODF. In Old-growth OMF, a moderate correlation was observed with burn severity and in secondary OMF. Distance to rivers had a negative moderate correlation in ODF and a positive high correlation in secondary OMF.

4. DISCUSSION

This study aimed to estimate carbon loss induced by fire in a Southeast AF protected area, considering LULC and influence of topographical, hydrological, anthropogenic and fire variables. Our hypotheses were that native forest areas, having greater biomass, were more impacted by fire and lost more carbon, which we have confirmed, and that slope, drought severity and burn severity influenced more carbon loss. However, we only verified this for burn severity with a moderate correlation.

Our results on carbon loss (23.35 MgC/ha) were larger than carbon loss related to LULC changes in 20 years period found by Pavani et al. (2018) in similar areas (1.37MgC/ha). These data exemplify that losses of carbon induced by deforestation and fires might be underestimated, as also evidenced in a fieldwork study in the Atlantic rainforest by Souza et al. (2022), being urgent to quantify them to have the real impacts of disturbances and LULC on carbon storage.

The old-growth ODF presented higher carbon losses, both due to its high carbon biomass and the largest burned area among the forest formations, highlighting the importance of disturbances that affect biodiversity and biomass of old-native forests (de Lima et al., 2020; Rosa et al., 2021). Although pasture areas have lower biomass and loose less carbon per hectare, the high numbers and area of burned fragments, in addition to the high percentage of carbon loss (90.4%) deserve attention, since there are forest fragments around (Guedes et al., 2020). Additionally, carbon losses in old-growth forests were similar among different forest types, despite seasonal, Dense and Mixed Ombrophilous forests have different compositions, biomass and ecological processes (IBGE, 2012). Old-growth forests lost more carbon than secondary forest, which might be associated to their succession status, adding importance to their conservation values.

As expected, the differences between the average carbon loss per hectare compared to the LULC classes indicated significant differences between the lowest and highest AGCB classes. Although the AGCB forest found in several field studies has similar values, the range values used in Equation 4 and Equation 5 are different in all LULC classes, as well as the NBR median, obtained by month/year/LULC, generated different values.

Considering the annual variations in total carbon loss, 2020 stands out for 25% of its areas losing carbon at values above 200 Mg C and 2014 for reaching the highest losses per hectare. In correlation analysis of LULC classes with drought severity, measured by the annual IDI, there was no significant correlation. In the same sense, IDI values that indicated that drought years had also more burnings and greater carbon loss, were valid only for 2003 and 2014, which together with 2001 and 2016 constituted severe drought. On the contrary, 2017 with few fires and few losses of carbon was a year of extreme drought (Cunha et al., 2019). Although drought events increase vegetation flammability (Alencar et al., 2006; Marengo et al., 2021) promoting a higher incidence of fires, they can decrease vegetation biomass (Yao et al., 2023). In the same study region, high occurrences of fire events and burning areas were more explained by drought in dry and wet seasons than by temperature, making a complex dynamic between fire events, burned area, environment, and climatic variables (Oliveira et al., 2023). Also, in years of extreme drought there would be little fire-induced carbon loss, considering that there have already been drought-induced losses.

Likewise, although carbon losses occurred mainly between July and December and there were variations between months, averages between them do not present significant differences. In June, in the dry season beginning, there is more fuel to burn and in December, during the return of rains, biomass develops again and makes fuel more available. Evaluating CS loss per hectare, seasonality had no influence. However, total loss data showed reduction in CS following fire seasons, which

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is worrying given the increasing in length of fire weather (IPCC, 2023; Jolly et al., 2015).

In rural sites, fires are used to renew pasture and agriculture sites (Brunel et al., 2021) and to clean trash and these fires may go uncontrolled to nearby forests. However, tropical forests can be highly damaged by fire-induced disturbances (Brando et al., 2014; Carvalho et al., 2022; Kelly et al., 2020; Loiselle et al., 2020; Pütz et al., 2011; Robinne et al., 2020; Sansevero et al., 2020). Native grasslands as HAG, for example, is a phytophysiognomy more prone to fire, in which even prescribed burning is discussed for its management (Aximoff et al., 2016; Motta et al., 2016).

5. CONCLUSION

As expected, forests presented larger fire-induced carbon loss than pastures and grasslands, a function of carbon storage capacity. Hence the need for care and protection of the remaining forest fragments. Slope and drought severity did not correlate with carbon loss, contrary to what we expected. However, even if moderately, burn severity confirmed our hypothesis, probably due to high biomass in ODF and OMF. Given the low number of related literature, our work contributes to filling a gap regarding fire and CS in Atlantic Forest, but there are still other issues that need to be addressed. Fieldwork in burned areas in the AF quantifying biomass or possible correlation variables would be important for better data validation. Fire is prohibited (Law nº 11.428/2006 - BRASIL, 2006), but it still happens and threatens ecosystem services. Our study, carried out in a small portion of this biome, in a protected area, has shown a high potential for fire-induced carbon loss, indicating a danger for the whole Atlantic Forest conservation and to international agreements of carbon emission reductions.

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AUTHOR CONTRIBUTIONS

Baião C. F. P.: Conceptualization, Methodology development, Software programming, Formal analysis, Investigation, Data curation and Writing - original draft; Massi K. G.: Conceptualization, Methodology development, Writing – review & editing and Project administration; Souza Junior W. C. de.: Writing – review & editing and Project administration.

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