ESCOLA SUPERIOR DE CONSERVAÇÃO AMBIENTAL E SUSTENTABILIDADE

CARBON SOURCE OR SINK? THE TURNING POINT FOR THE FRAGMENTED LANDSCAPES OF ATLANTIC FORESTS

Por

THAIS DE CASSIA ARAUJO ROBERTS

NAZARÉ PAULISTA, 2022

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COMITÊ DE ORIENTAÇÃO

PROF. DR. RICARDO GOMES CÉSAR
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TRABALHO FINAL APRESENTADO AO PROGRAMA DE MESTRADO PROFISSIONAL EM CONSERVAÇÃO DA BIODIVERSIDADE E DESENVOLVIMENTO SUSTENTÁVEL COMO REQUISITO PARCIAL À OBTENÇÃO DO GRAU DE MESTRE

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Nazaré Paulista, 09 de agosto de 2022.

Prof. Dr. Ricardo Gomes César

Prof. Dr. Alexandre Uezu

Prof. Dr. Alexandre Camargo Martensen

Dedico esse trabalho para a paisagem do *Continuun* Cantareira e a toda população que nela habita e usa seus recursos naturais.

“It’s not just the land that is broken, but more importantly, our relationship to land…we can’t meaningfully proceed with healing, with restoration, without “re – story - action.” In other word, our relationship with land cannot heal until we hear its stories. But who will tell them?”

(Robin Kimmerer)

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CARBON SOURCE OR SINK? THE TURNING POINT FOR THE FRAGMENTED LANDSCAPES OF ATLANTIC FORESTS
Por

Thais de Cassia Araujo Roberts

Agosto, 2022

Orientador: Prof. Dr. Ricardo Gomes César

Palavras-chave: *estoque de carbono, floresta tropical, biomassa acima do solo, transição florestal, mudança de uso e cobertura da terra.*

O histórico do uso da terra e dinâmica dos estoques de carbono na escala da paisagem revelaram que agora é o momento decisivo para que as paisagens altamente fragmentadas da Mata Atlântica se tornem um sumidouro de carbono por meio de ações de manejo, conservação e restauração, caso contrário, se tornará uma paisagem emissora de carbono. Analisamos a dinâmica da mudança da cobertura e uso da terra de 1985 a 2020 e avaliamos os estoques de carbono de quatro tipologias: plantio de eucalipto de ciclo curto, pastagem, floresta nativa madura e floresta nativa secundária. As estimativas médias de carbono das tipologias foram combinadas com mapas de cobertura do solo, resultando no fluxo de estoques de carbono ao longo dos anos. Apesar da relativa estabilidade da cobertura florestal nativa durante este período (44%-42% em 1985 e 2020 respectivamente), a perda contínua de florestas nativas antigas (44%-34% em 1985 e 2020 respectivamente) foi encoberta pelo ganho de cobertura florestal nativa secundária (0 - 8 %). O estoque de carbono variou conforme a idade da floresta, o valor médio de CO_2 eq estocado nas florestas nativas antigas (410,3 ± 103,8 Mg ha^{-1}) foi aproximadamente o dobro da floresta nativa secundária (221,78 ± 176 Mg ha^{-1}). Por outro lado, as estimativas revelaram que mesmo as florestas nativas

secundárias são mais eficientes que o eucalipto e as pastagens na capacidade de armazenar carbono. O estoque total de CO_2 eq estimado na paisagem de 1985 a 2003 diminuiu devido ao desmatamento, causando um balanço negativo de carbono de 6,5 Tg CO_2 eq. No entanto, de 2003 a 2020, o estoque total da paisagem manteve-se estável devido à desaceleração do desmatamento e à regeneração da floresta nativa secundária, alcançando a neutralidade de carbono. Apesar do histórico de degradação e perda das paisagens da Mata Atlântica, a dinâmica do uso da terra mostra um processo de transição florestal. Se projetado adequadamente, pode reduzir o desmatamento, mitigar a insegurança hídrica e alimentar, reverter a tendência dos hotspots e promover a adaptação baseada no ecossistema às mudanças climáticas.

ABSTRACT

Abstract do Trabalho Final apresentado ao Programa de Mestrado Profissional em Conservação da Biodiversidade e Desenvolvimento Sustentável como requisito parcial à obtenção do grau de Mestre

CARBON SOURCE OR SINK? THE TURNING POINT FOR THE FRAGMENTED LANDSCAPES OF ATLANTIC FORESTS

By

Thais de Cassia Araujo Roberts

August, 2022

Advisor: Prof. Dr. Ricardo Gomes César

Key words: *carbon stock, tropical forest, aboveground biomass, forest transition, land use land cover change.*

Historical land use and the carbon stocks' dynamics at the landscape level revealed that now is the decisive moment for the highly fragmented landscape of Atlantic forests to become a carbon sink through management, conservation, and restoration actions. However, if no action is taken, it will become a carbon source landscape. We analyzed the land use, land cover change dynamics from 1985 to 2020, and assessed the carbon stocks of four typologies: short rotation eucalyptus plantation, pasture, old-growth native forest, and secondary native forest. The mean carbon estimates of typologies were combined with land cover maps, resulting in the flux of carbon stocks over the years. Despite the relative stability of native forest cover during this period (44% and 42%, 1985 and 2020 respectively), the ongoing loss of old-growth native forests (44% and 34%, 1985 and 2020 respectively) has been covered by the gain of secondary native forest cover (0 - 8%). The carbon stocks varied according to the age of the forest, the average value of CO_2 eq stocked in old-growth native forests (410.3 ± 103.8 Mg ha^{-1}) was double that of the secondary native forest (221.78 ± 176 Mg ha^{-1}). On the other hand, the estimates revealed that even the secondary native forests are more efficient than eucalyptus and pasture in their capacity to store carbon. The total landscape stock

of CO_2 eq estimated from 1985 to 2003 declined due the deforestation, causing a negative carbon budget of 6.5 Tg CO_2 eq. However, from 2003 to 2020, the total landscape stock kept stable due to a slowdown in deforestation and regrown of the secondary native forest, achieving carbon neutrality. Despite the history of degradation and loss of the Atlantic forest landscapes, the land-use dynamics show a forest transition process. If properly designed, it can reduce deforestation, mitigate water and food insecurity, reverse the hotspot trend and promote ecosystem-based adaptation to climate change.

1. **INTRODUCTION**

Mismanagement of land use compromises ecological processes and as a consequence, the climate as well as the people. On the other hand, it is in the land use management that we will find solutions to feed humanity, conserve ecosystems and hold the global average temperature below 2°C (Shukla et al., 2019). However, these desirable outcomes are dependent on locally appropriate policies and governance systems.

In highly dynamic landscapes such as some tropical regions, ecosystems goods and services delivery can be affected not only by the present landscape structure, but also by the historical land use (Ferraz et al., 2014; Lira, Ewers, et al., 2012). In such regions, the landscape matrix is dominated by anthropogenic activities, with the natural ecosystem consisting of small and isolated fragments (Ribeiro et al., 2009; Tabarelli et al., 2008). In this context, remnant fragments may be composed of forests of different ages, depending on the history of use and disturbance they experienced (Lira, Ewers, et al., 2012). Together, forest loss, fragmentation, degradation and regeneration processes have transformed these landscapes into a heterogeneous mosaic of forest remnants in different successional stages.

The continuous tropical Atlantic forest that originally covered the Brazil coast, has been transformed by agricultural and urban expansion over the past 500 years (Dean, 1996). Only 11,7% of Atlantic forest cover remains, into many small fragments, and very few old-growth remnants (Ribeiro et al., 2009). Despite the extensive historical devastation of the Atlantic forest, recent studies have suggested that, over the past three decades, this biome has been experiencing gain in forest cover through a natural regeneration (Costa et al. 2017; de Rezende et al. 2015).

Different forest regrowth process, mediated by social, economic and ecological outcomes (Rudel, 2012), are also affecting the quality and age of forest fragments (Lira, Ewers, et al., 2012) and thus affecting all ecological processes associated with those fragments (Lira, Tambosi, et al., 2012). A meta-analysis of second-growth tropical forests observed that these primary forests may take approximately 80 years to fully recover above-ground biomass levels, while species richness may take centuries

(Martin et al., 2013; Poorter et al., 2016). The same holds true for ecosystem services, which may rely on structurally complex forests to be maximized (Chazdon et al., 2016; Wilson et al., 2017).

Global climate change projections indicate the carbon stocks and sequestration as one of the most important ecosystem services. The benefit of carbon storage refers to the retention on carbon stocks in reservoirs, and in consequence, avoid release of carbon into the atmosphere. The benefits of carbon storage comes from the magnitude, longevity, stability and timing of the ecosystem carbon stocks (Ajani et al., 2013; Mackey et al., 2013).

The magnitude refers of the net carbon balance and the area of the ecosystem. Longevity refers to the period that the carbon stock remains at a giving level, and effects of natural disturbances and regenerations. The stability depends of the maintenance integrity of the ecosystem, and includes resistance, resilience and adaptive capacity. The timing refers to the fact that avoiding emissions now is better than future sequestration, as carbon stocks are quickly depleted by land-use impacts but only slowly regained (Martin et al., 2013; Poorter et al., 2016).

Policy decision about management of ecosystem processes will be good if the information that supports these decisions are good. A more integrated approach to carbon accounting is needed in order to achieve the full potential of natural based solutions, which prioritize the most effective options. Accounting needs to include stocks as wells as flows, identify ecosystem condition, track changes overs time, attribute impacts of ecosystem loss and degradation, and demonstrate the interdependence between ecosystem and human well-being (Keith et al., 2021).

We estimated the carbon stock capacity at the landscape level, and analyzed how the dynamics of land use and land change cover affected these stocks in the last thirty-five years in a highly fragmented landscape of Atlantic forest. Specifically we analyzed the land use cover and land use changes dynamics from 1985 to 2020 at the landscape level. Estimate the aboveground carbon stock of the different typologies, and estimate the total carbon stock and flux over the years by the land use and land cover changes maps. We highlight the amount of carbon released and sequestrated due to changes in the landscapes dynamics. Our approach to carbon accounting provides the kind of information needed to better understand the benefits, trade-offs and options for nature based solutions actions, and effectively achieve mitigation and adaptation outcomes, providing for more transparent and evidence-based decision-making.

2. **MATERIALS AND METHODS**

2.1. *Study region*

The study region is situated in the Atlantic Forest biome, a highly diverse and endangered tropical forest (Joly et al., 2014), one of the most emblematic global hotspots for conservation priorities (Laurance, 2009). The biome has a long history of land-use changes and widespread deforestation. The forest was reduced to 12% to 16% of its original cover resulting in a highly fragmented landscape, with more than 80% of its remnant forest cover reduced to small fragments (Ribeiro et al., 2009) in a landscape dominated by an anthropogenic matrix.

The study landscape is an area of 391,584 ha, located in the state of São Paulo, 50km north of the capital. The landscape covers a mountain ridge region, delimited by the area of contribution of the Cantareira System water supply, the Cantareira Environmental Protected Area (sustainable-use), the Guarulhos State Forest (sustainable-use), and five strict-use protected areas: Cantareira State Park, Itaberaba State Park, Itapetinga State Park, Alberto Löfgren State Park, and Pedra Grande Natural Monument. Together, they form a mosaic of protected areas, known as the Canateira *Continuum* (Fig.1). This area was created for the purposes of security, maintenance, and quality of the water supply in the Cantareira System. The Cantareira System is a large complex of five interconnected reservoirs, that provide freshwater to the metropolitan area of São Paulo city, that houses around 9 million people (Uezu et al., 2017). In addition to the safety of the water supply, this area also includes an important ecological corridor that was considered of high priority for biodiversity conservation at the state level (Joly et al., 2010; Rodrigues & Bononi, 2008).

According to the Köppen classification, the climate is Cwb – humid subtropical, dry winter and mild rainy summer (Alvares et al., 2013). Annual precipitation average is 1.500mm, with more rainfall occurring in the higher altitudes (*INMET - 1981-2010*, 2011). The forest predominant formation of Dense Ombrophilous Forest.

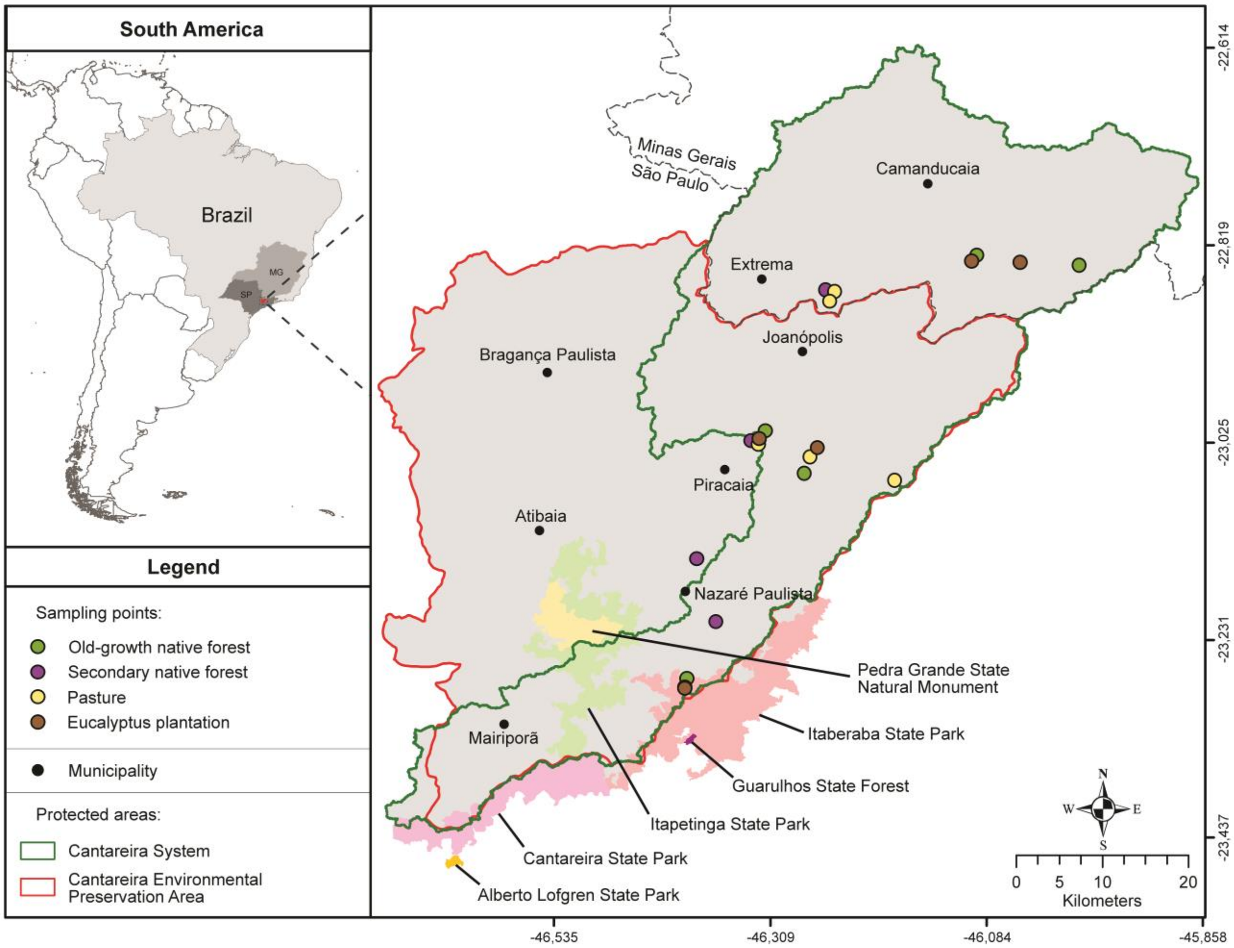

Fig. 1. Location of the study landscape and sample plots delimited by the mosaic of protected areas, the Cantareira *Continuum* and the Cantareira system in São Paulo, Brazil.

The landscape in the study region is heterogeneous, with a unique composition distributed in small properties with varied land uses consisting of pasture, eucalyptus plantations and native Atlantic Forest. The pasture areas, in general, are degraded with low productivity and susceptible to the soil erosion process. Eucalyptus plantations have been intensively managed in short rotations (~5-7 years) and extensive monocultures. Companies for production of the wood destined to pulp predominate in the northern region of the landscape. In the south, small properties plant eucalyptus to use the wood as biomass fuel (less intensively managed). The region is also affected by an intermittent population that has vacation homes, due to its proximity to the capital of São Paulo state.

Native forest cover in the study area is characterized by few old-growth native forest fragments and numerous small and medium patches of second growth forest. In recent decades, the Atlantic Forest has experienced a process of regeneration in some regions (Costa et al., 2017; de Rezende et al., 2015) resulting from socioeconomic factors and political actions for environmental protection. Together, deforestation, fragmentation, degradation, and regeneration processes have transformed this ecosystem into a heterogeneous mosaic of forest remnants in different successional stages.

2.2. *Land use, Land Cover Change (LULCC)*

We used the LULCC data from the sixth collection of MapBiomas, a Brazilian Annual Land Use and Land Cover Mapping Project (MapBiomas 6^{th} Collection). This dataset reconstructs annual LULC information at 30-m spatial resolution from 1985 to 2020 for every Brazilian biome.

The MapBiomas project is an important tool for understanding forest dynamics using medium-resolution remote sensing data with detailed land use classification. The MapBiomas analyses of accuracy for the Atlantic Forest, in the most detailed level (level 3), indicate a global accuracy of 85.5%, with an allocation disagreement of 7.6%, and an area disagreement of 6.9%, with consistent accuracy for the entire time series. The accuracy analysis uses the population error matrix and the global, user, and producer accuracies.

For Land use and land cover change analysis, we selected the maps of the years 1985, 1989, 2003, and 2020. In order to simplify the map, the legend was reclassified with the land uses with high representativeness found in the landscape, and the categories with low representativeness were included in one category, as follow: Old-growth native forest, secondary native forest, Eucalyptus plantation, Pasture, Urban area, Water and Others (croplands, mining, other non-vegetaded areas and rock formations).

For this study, two maps of LULCC were produced using ArcGis 10.7.1, and with the data from the area of change, two transition matrices were produced for the analyzed periods, 1985 - 2003 and 2003 – 2020 (supplementary materials). These transition matrices accurately communicate the values reported on the LULCC map and can indicate the rates of change in a landscape as well as the categories that prevailed.

2.3. *Estimation of carbon stocks*

Above ground biomass (AGB), is the most easily manipulated carbon pool in carbon forest projects. In several studies the above ground biomass in native forests has been estimated from data obtained in field surveys of vegetation, including: species, diameter of trees, total height of tree, and wood density (Brown et al., 1989). In this research, we estimated the AGB of the land-use typologies. Four typologies of land use were considered: eucalyptus plantation, pasture, old-growth native forest and secondary native forest. The two classes of native forest were defined by analyzing LULCC maps. We estimate age and previous land use of existing native forest cover by overlaying land-use classifications maps (1985, 1989, 2003 and 2020).

The existing native forest cover in the 1985 map, with more than 30 years, was considered old-growth native forest, and the native cover first detected from 1989 forward, was considered secondary native forest.

2.4. *Field survey*

In the secondary native forest (< 30 years), we located sampling plots on second growth native forests, that were established without human assistance (naturally regenerative) on pasturelands, with a path size of at least 5 ha, and with a possibility to install a 30 x 30m plot and have around 40m of the border on each side, in order to avoid the edge effect. We estimate that the sampled secondary native forests were 10 – 29 years old.

We identified old-growth native conserved forests (forest that standed since 1985, ≥ 30 years old), with no evidence of disturbance, protected from human and cattle encroachment, and belonging to relatively large forest areas (> 100 ha).

In the eucalyptus plantation, we located the sampling plots on plantations that were between 5 and 7 years old, because the eucalyptus is regularly harvested at that age.

We installed a 30 x 30 m (900 m²) plot to gather vegetation data in five sites of old-growth native forests, four of secondary native forests, five in pastures, and six in eucalyptus plantations, a total of 20 plots. In each typology, the field plot was randomly allocated in the landscape, subject to access permission from landowners.

In each plot of native forest, we measured the diameter at breast height (DBH), total tree height and identified to the specie level whenever possible all living rooted trees and shrubs DBH ≥ 5 cm by sending the sampled material to the Superior School of Agriculture Herbarium (ESA-ESALQ) at the University of São Paulo.

In the eucalyptus plantation, we measured in each plot, the diameter at breast height (DBH) of all living trees and shrubs DBH ≥ 5 cm and the total height of 15 trees. The set of height values of the individual samples measured with their respective diameters were used to establish a hypsometric relation (height ~ DBH), applied to estimate the heights of the other trees on the plot. In each plot of pasture plots, we trimmed all the aboveground grass in four squares of 0.5 x 0.5m, dried it until constant weight, and measured its dry biomass with a high precision scale.

2.5. *Data processing*

To estimate the height of the eucalyptus stem, mathematical models found in the literature were tested, and adjusted as a function of DBH, specifically for the data set of each plot. After testing several mathematical regression models, the adjusted model of Curtis was the best fit for the DBH-height relationship of 19 and 20 plots. Similarly, in plot 21 and 24 the adjusted model of Curtis was the one with the best representation of the DBH-height relationship (supplementary materials).

The Eucalyptus plantation is not static, there is stands growing in diferentes ages, and also harvesting, due these dynamics at a landscape level, the average carbon stock in the Eucalyptus plantations of short rotations was estimated considering the annual carbon storage (1^{st} to 6^{th} years), the biomass loss due to the harvesting (7^{th} year) was also included in the quantification of the average carbon stock (VCS Guidance: Harvesting, 2011). We use the Software SisEucalipto (Oliveira, 2021) to calculate the estimates of carbon stock for each year by plot (supplementary materials), and validated with a specific equation adjusted locally to estimate carbon stock on total stem on Eucalyptus spp trees (Soares & Oliveira, 2002).

The large area covered by the study harbors an altitude gradient and terrain inclination that favors physiognomic variations of tropical forests. Due to this variation, it is believed that a more comprehensive equation, but with a level of species specificity, for the calculation of biomass would be the most suitable for this study. ABG of each stem was calculated using the equation developed by CHAVE *et al.* (2014) that requires wood density. Data on wood density was obtained from (Zanne et al., 2009).

Wood density estimates for species not included in these databases were estimated as follows: the average of the species of the same genus on the study site, or the average of species of the same family on the study site. For the species identified only to the genus or family level, we followed the steps mentioned previously. For the unidentified species, we considered wood density as the average density of all species sampled in the study site.

The CO_2 eq stock in megagrams per hectare (Mg ha^{-1}) was calculated from the sum of the CO_2 eq sampled tree by the plot area (supplementary materials). Therefore the estimates values of CO_2 eq stock for the four typologies were calculated from the means and the confidence interval of 95%, of the data sampled. The CO_2 eq stock estimates mean was compared among the typologies using ANOVA, in the process was verified normality of residuals distribution and homogeneity of variance, and it didn’t find normality neighter homogeneity, so, we conduct a logarithmic transformation, and the Shapiro-Wilk test showed normality of residuals distribution (p = 0.55) Bartlett’s test showed homogeneity of variance (p = 0.31).

Estimates of carbon flux through changes in land use in tropical regions are derived from models that depend on the estimate of biomass in forests (Brown & Lugo, 1992). The amount of biomass in a forest determines the potential for carbon storage as 1 Mg of biomass is equivalent to 0.47 Mg of carbon (14 - AR-TOOL, 2013), which could be released into the atmosphere due to land use changes. The results will be expressed in terms of emissions of carbon dioxide equivalent (CO_2 eq) stock, and for this, the megagrams of carbon will be multiplied by the ratio of the weights of carbon dioxide (14 - AR-TOOL, 2013).

The dynamics of carbon fluxes were quantified in relation to gains and losses in forest cover for each period. Finally, the above-ground carbon emissions were quantified as a result of the difference between the release and removal of carbon in the studied period. Vegetation cover gains were considered as forest regeneration or conversion to eucalyptus and the value assigned to these areas. To quantify the carbon released and removed from the region, the average carbon stock value of the vegetation present in a given location before deforestation was calculated.

3. **RESULTS**

3.1. *Land use dynamics at the landscape level*

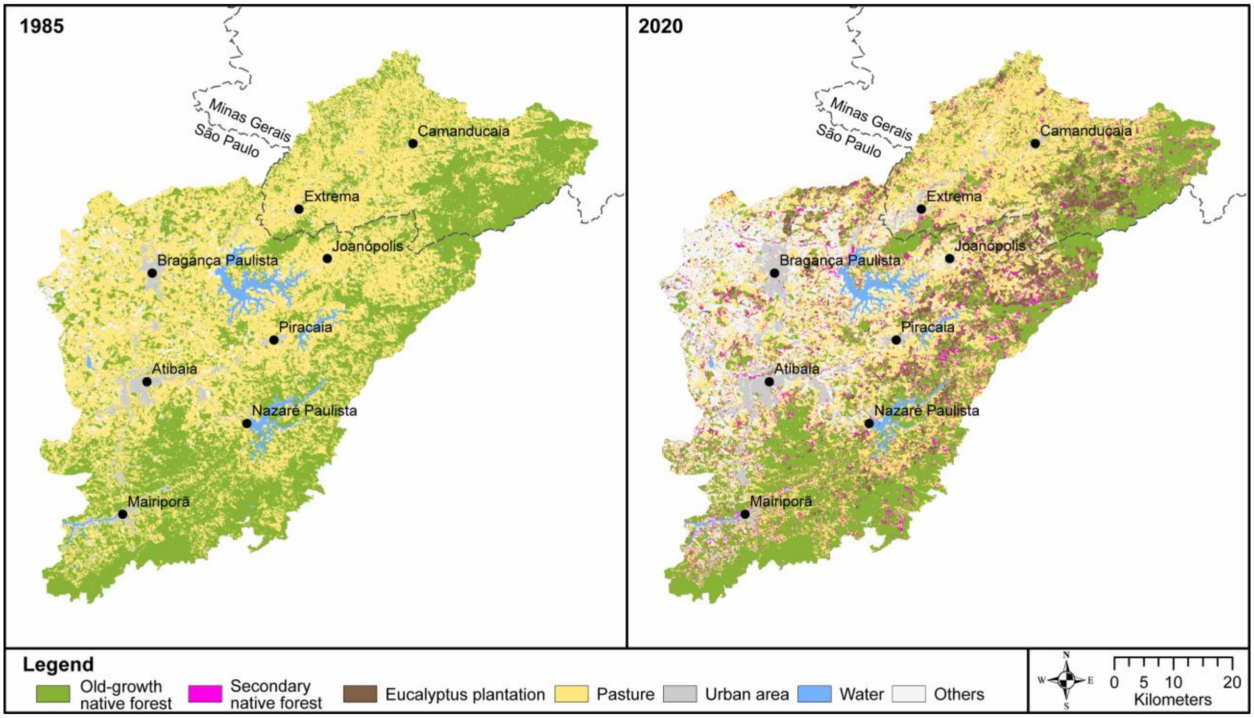

Fig. 2. Land use and land cover Maps of the studied landscape of the first and final year of the analyzed period. Source: MapBiomas (https://plataforma.mapbiomas.org).

Native forest cover appears net stable, but this relative stability hides a dynamic process with detrimental effects on carbon stocking and ecosystem services. When native forest cover loss and gain are mapped over the years, we realized that stability does not exist and old-growth forests are being deforested while secondary native forests regenerates in other areas (Fig. 2).

Old-growth native forest cover ranged from 172 thousand ha to 143.5 thousand ha, between 1985 and 2003, respectively, reaching its lowest level in 2020 with 135 thousand ha. While secondary native forest cover has attained an increase in recent years reaching 32 thousand ha in 2020. Old-growth forest cover has declined in the period, while the net native forest cover kept stable (~44%-42%), which indicates that the ongoing loss of older native forest cover (34% in 2020) has been compensated in terms of area by the increase of secondary native forest cover (8%) (Fig.3).

The spatiotemporal stability of native forest cover seems to be directly associated with the dynamics of agro-pastoral land uses in the region. While the area of other uses tripled and the area of eucalyptus plantations expanded from 0 in 1985 to ~24 thousand ha in 2020 in the past 35 years, the area of pasturelands declined by 41% (~76 thousand ha) (Fig. 4). As a consequence of such historical transformation, the current area of anthropic land uses (eucalyptus plantations, croplands, pasture, urban area, and mining, excluding water reservoirs) is 216.3 thousand ha (55%), which represents an increase of ~2.6% (~5.5 thousand ha) since 1985. Thus, native forest cover has remained almost stable in the last 17 years because other uses have expanded mostly over pasturelands.

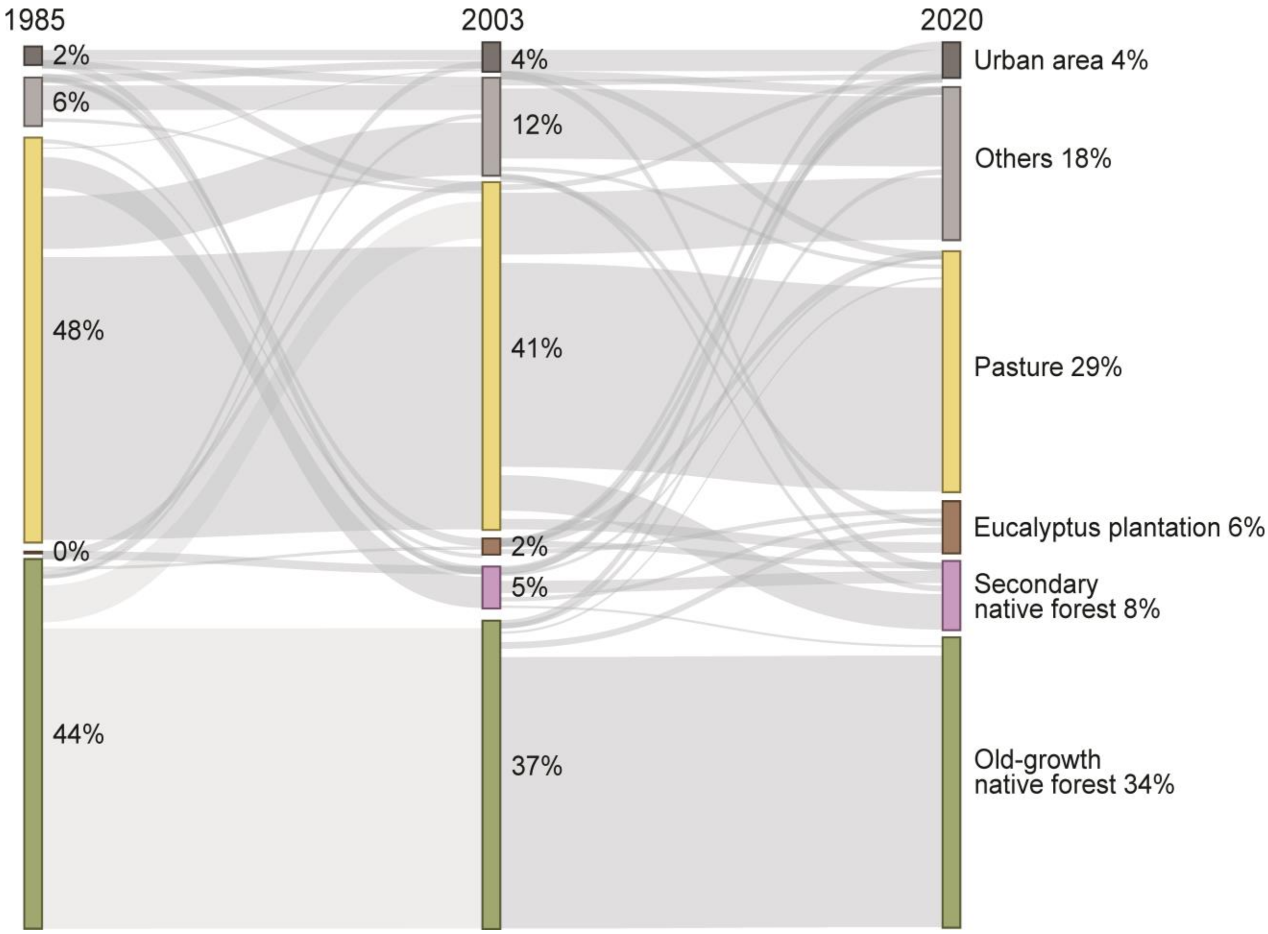

Fig. 3. Conversion flux of land use and land cover over the years at the landscape level.

The areas of native forest cover loss were occupied mostly by pasture (73%) and eucalyptus plantations (18%) from 1985 to 2003, and were recently occupied mostly (between 2003 and 2020) by eucalyptus plantations (51%) and pasture (37%). Native forest gain occurred mostly in areas that were once occupied by pasture (97%) in the period analyzed.

3.2. *Temporal carbon dynamics*

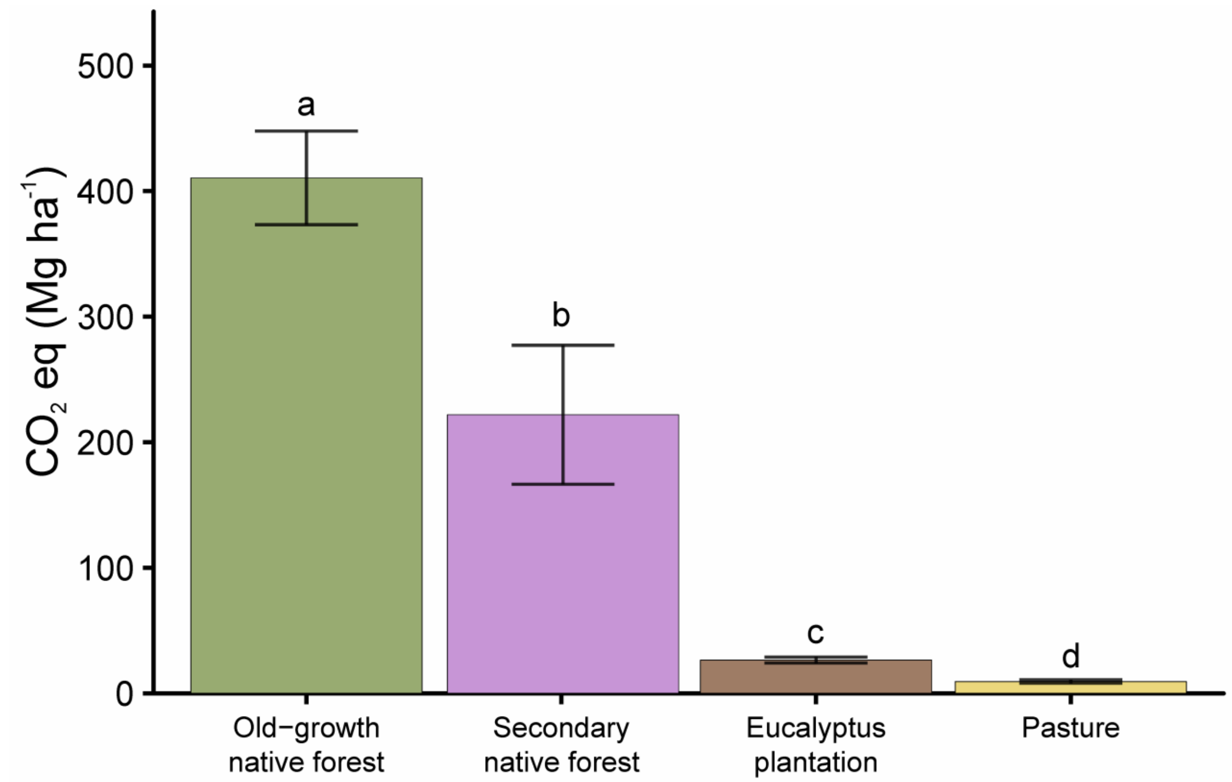

Fig. 4. CO_2 eq means estimates of the typologies with the errors bars representing 95% of confidence intervals. The letters above the bars indicate they differ statistically (ANOVA p <0.01).

The results of CO_2 eq estimates for old-growth native forest and secondary native forest showed that the age of the forest makes a difference in terms of carbon stock dynamics. Carbon stocks among all typologies differed (ANOVA, p = <0.01) (Fig.4). The average value of CO_2 eq stocked in the AGB of old-growth native forests was 410.3 ± 103.8 Mg CO_2 eq ha^{-1}, almost double of the secondary native forest 221.78 ± 176 Mg CO_2 eq ha^{-1} (Fig. 4). On the other hand, the estimates of CO_2 eq stored in short rotation eucalyptus plantation and pasture (26.4 ± 6.1 Mg CO_2 eq ha^{-1} and 9.3 ± 3.7 Mg CO_2 eq ha^{-1}, respectively), revealed that even the secondary native forests are more efficient than the intensively managed eucalyptus plantation and pasture in their capacity to store carbon (Fig. 4).

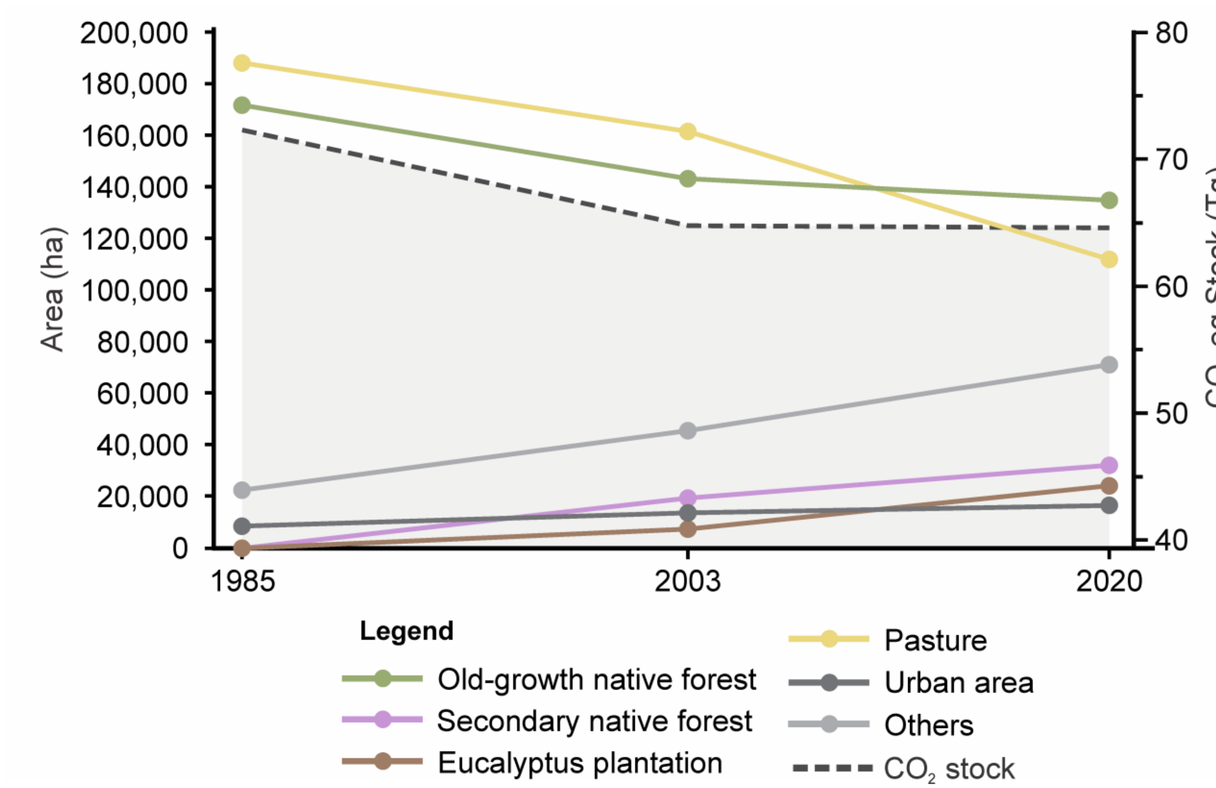

Fig. 5. Historical changes in the land use cover and total carbon stock at the landscape level. The dashed line refers to CO_2 stock changes along time.

The land use change between deforestation of old-growth native forest and regrowth of secondary native forest reduced the landscape carbon stocks along time, even though native forest cover remained constant. The total landscape stock of CO_2 eq on AGB estimated in the period of 1985 – 2003, declined from 72.3 Tg to 64.9 Tg CO_2 eq, causing a negative carbon budget of 7.4 Tg CO_2 eq (Fig. 6), however, from 2003 – 2020, the total landscape stock was kept stable, almost achieving the carbon neutrality (change of 64.9 Tg CO_2 eq to 64.25 Tg CO_2 eq) (Fig. 5 and 6). The carbon emissions, marjority from deforestation of old native forests (6.64 Tg CO_2 eq) were compensated by the uptake of the regrowth of the secondary native forest (5.97 Tg CO_2 eq) (Fig. 6). The native forest is the major carbon storage of the landscape with more than 97% of its storage in the tree biomass. In the current landscape (2020) 86% (55.4 Tg CO_2 eq) of the carbon is stored in the old-growth native forest and 11% (7.14 Tg

CO_2 eq) of the carbon is stored in the secondary native forest. Only 22% of the carbon stored in the old-growth native forest are in the protected areas and the others 78% are in the private lands. These areas represents only 7.6% (29,908 ha) of the landscape studied territory and is responsible for 12.27 Tg CO_2 eq.

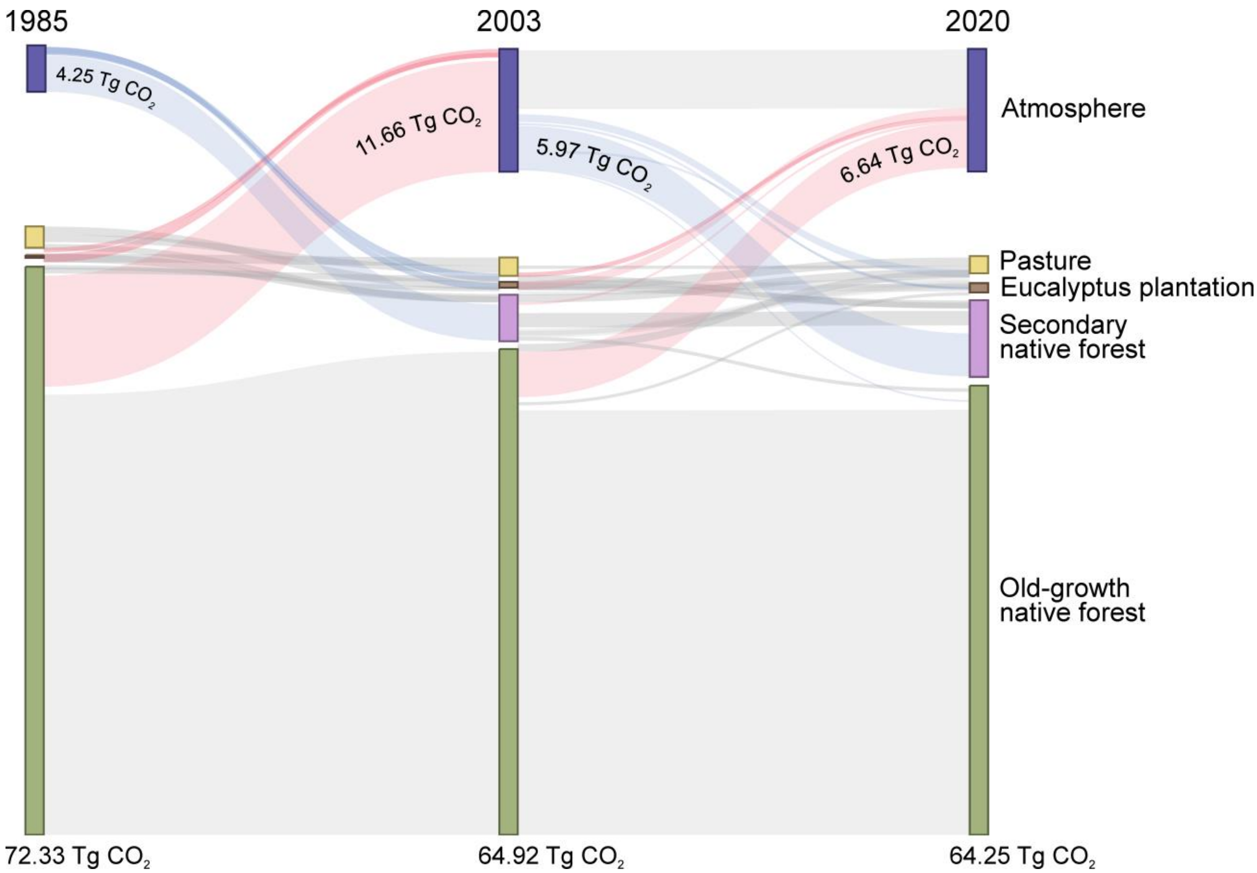

Fig. 6. Carbon stock and flows over the analyzed years due the land conversion. In purple, the sequestration amounts and in pink, the emissions.

4. **DISCUSSION**

4.1. *Land-use dynamics*

Human-modified landscapes are usually submitted to intensive dynamics of land use and land cover changes (Tabarelli et al., 2012). In our study the native forest cover remained stable despite the loss of old-growth native native forest cover, due to the natural regeneration of secondary native forest. This confirme trends observed in other Atlantic Forest regions (Costa et al., 2017; Ferraz et al., 2014; Lira, Tambosi, et al., 2012; Metzger et al., 2009; Teixeira et al., 2009) and recently for the whole Atlantic Forest area (Rosa et al., 2021). The continuous substitution of the old-growth native forest by regenerating secondary native forests will likely lead to landscapes with less biomass (Groeneveld et al., 2009; Martin et al., 2013) and the result could represent a decrease in other ecosystem services delivered by forests, even if native forest cover remains the same.

However, the recent increase of secondary native forest cover in the landscape and a decrease in the deforestation rates is clear evidence of the second stage of the forest transition, according to the environmental Kuznets curves, after previous periods of high forest loss followed by the intense reduction of deforestation rates and consequent forest stabilization (Rudel et al., 2005) (Fig. 5).

The expansion of forest transition has brought hopes for the recovery of tropical forests (Rudel, 2012) including in Brazil (Baptista & Rudel, 2006; Costa et al., 2017; Perz & Skole, 2003). Brazil has considerably strict legislation to protect forests and mandates forest recovery on private lands (Brancalion et al., 2016). In addition, the Atlantic Forest has specific legislation to protect all forest patches from intermediate successional stages (> 10 years old) from deforestation. Such legal protections, alongside the social and economic development of several regions within this biome, have contributed to forest transitions regionally (Baptista & Rudel, 2006; Costa et al., 2017; Lira, Tambosi, et al., 2012).

These landscape dynamics should be carefully observed since most of the initiatives are focused on increasing forest cover, they also need to conserve old-growth native forest fragments and increase forest quality (Ferraz et al., 2014).

Old-growth native forests are thus, continuously being degraded and lost, and despite the net stability of forest cover, there is an important and continuous net loss of forest quality. The Atlantic Forest has very few old-growth remnants (Ribeiro et al., 2009). In the studied landscape 28% of the remaining old-growth native forest are in the strict-use protected areas, and the others 72% are privately owned, and more susceptible to anthropogenic disturbances and loss.

Given that law enforcement is relatively effective in this region, we believe that most old-growth native forests may have been lost, not only by deforestation, but also through intense degradation, and fires in neighboring pasturelands (Brunel et al., 2021; Dean, 1996). The presence of intense anthropogenic disturbances is recognized as important in driving old growth into initial successional stages (Santos et al., 2008; Tabarelli et al., 2008) and the main driver of carbon stocks loss (Pyles et al., 2022).

We acknowledge, however, that our typology " old-growth native native forests " is not entirely composed of older growth forests, and an important, part of it can be potentially represented by native forest cover <35 years old, which regenerated a few years before the first available Landsat image in 1985 used in the present analysis.

The main land-use transitions observed in the landscape were the loss of old-growth native forests to pasture and the regeneration of secondary native forests in abandoned pasture. Pasture landscapes were more dynamic than any other land use. This occurs in extensive cattle ranching, in which marginal lands are occupied and low investments in the production system are made. Given that this production model does not require flat terrain or suitable soil conditions to be implemented, and are usually not maintained by landholders, both the conversion of forest to pastureland and the regeneration of forests over abandoned pasturelands are more frequent.

The increase in eucalyptus plantation cover was observed in the landscape, and in Brazil mostly for pulpwood, but also round logs, sawn lumber, firewood, charcoal, fencing poles, and oil such flexible uses and high productivity makes eucalyptus popular commercial trees for farmers (Brancalion et al., 2020; Gonçalves et al., 2013). Most of these plantations have been intensively managed in short rotations (~5-7 years) and extensive monocultures, which prevent the natural regenerations of native wood species and resulted in the "green deserts" (Bremer & Farley, 2010). However, less intensively managed and abandoned eucalyptus plantations in many regions host a high diversity of plants and birds (Cesar et al., 2018; Lopes et al., 2015).

4.2. *Carbon stocks and fluxes*

Our analysis estimating CO_2 eq in the forests AGB showed that the age of the forest makes difference in the CO_2 eq stocked on AGB, other studies have found the similar results for landscape and region level (Alves et al., 2010; Becknell et al., 2018; Ditt et al., 2010; Vieira et al., 2011). Although, we acknowledge, that we may be overestimating the total CO_2 eq stocked, on this highly fragmented landscape since we avoided edge and highly disturbed areas, well known for lower carbon stocks than the average (de Lima et al., 2020; Pütz et al., 2014; Romitelli, 2014, 2019).

The CO_2 eq in the AGB results of the forests varied widely among the plots in the same typology, especially for those of secondary native forests. Studies of Neotropical second-growth forests have shown wide variation in aboveground biomass recovery, at both regional and landscape scales that is mainly explained by age, slope and distance to anthropogenic features (Becknell et al., 2018; Poorter et al., 2016; Rozendaal et al., 2017).

Based on a regional model, second-growth Neotropical forests with 1500mm of rain per year, like those in our study should accumulate ~193.66 Mg CO_2 eq ha^{-1} of AGB in the first 20 years of regeneration (Poorter et al., 2016), corresponding to a net carbon uptake of 11.18 Mg CO_2 eq ha^{-1} year. This suggests that Atlantic forests in this study area, should reach 90 percent of mature levels of biomass as fast as the average second-growth Neotropical forest (~66 years) (Poorter et al., 2016) and that regeneration has not been significantly inhibited by the legacy of past land use.

Because of the history of disturbance of Atlantic forest by humans over the past 500 years (Dean, 1996), is rare to find a pristine forest and a reference area for carbon storage. Therefore, the maximum capacity of carbon storage is unknown. Both classes of native forest that have been studied are second-growth forests and their biomass is probably still increasing. If these forests remain conserved, in the future their average AGB carbon stock may be higher than estimated.

Forests and landscapes are not static, they are constantly changing, resulting in large temporal changes in carbon fluxes and storage. Three driving forces for these changes often act together (Pan et al., 2009), changes in the environment, natural disturbances, and management practices. The last one plays an important role in this study landscape, fire is widely used by farms in Brazil during the winter, or the dry season to remove accumulated dead pasture biomass, into nutrient-rich ash, that stimulates regrowth of pasture (Brunel et al., 2021; Csiszar et al., 2012; Dean, 1996).

The eucalyptus plantations have been intensively managed in short rotations (~7 years) and extensive monocultures, and it's carbon stock in the landscape is low (Fig 6). The fact is the areas that were harvested and regrowing can't contribute with the carbon stock, resulting in a small value net carbon (Fig. 4), these practices have substantial impacts on the short-term landscape carbon dynamics. However, eucalyptus plantation have an important role in the CO_2 eq sequestration (Sanquetta et al., 2018), because it's relative growth rate is high.

Although the land covered by the native forests is responsible for 95% of the carbon stock in the landscape, it is as much important for the local carbon stock, as tropical forest are important for the global carbon cycle (Pan et al., 2011). So important for the carbon stock, that any changes in the forest cover would affect deeply the landscape carbon cycle. From 1985 through 2003 the deforestation of a big portion of the land, cause an expressive decrease in carbon stock. However, a significant slowdown in deforestation in the landscape happened after 2003, and the gains in secondary native forests were offset by the little losses of old-growth native forests, almost achieving carbon neutrality.

4.3. *Implications for practice*

If all the areas of old-growth native forest are conserved and secondary forests keep untouched, for 30 years, the landscape will have a big potential to achieve a carbon sink status, with total carbon stock of 72.61 Tg CO_2 eq. The net carbon uptake is ~11.18 Mg CO_2 eq ha^{-1} year, for growing forests of 10 - 32 years old (Becknell et al., 2018; Poorter et al., 2016). A meta-analysis of second-growth tropical forests, observed that may take about 80 years to fully recover above-ground biomass levels of primary forests, while species richness may take centuries (Martin et al., 2013; Poorter et al., 2016). The same holds for ecosystem services, which may rely on structurally complex forests to be maximized (Chazdon et al., 2016; Wilson et al., 2017).

Therefore, if no action for the conservation of the forest can be made, the carbon stock will decrease. The conservation of the Atlantic forest carbon stocks is highly dependent on avoiding forest degradation, which can generate carbon losses 30% higher than any future climate change. As well, it is threatened by climate changes, specifically in temperature (Pyles et al., 2022).

We highlight the critical need to develop policies that guarantee the conservation of old-growth native native forests. Forests provide a myriad of environmental and social benefits in the landscape beside carbon mitigation. The adaptation, through local climate regulation services, contribute significantly to solve the extreme heat due climate change by the biophysical effects of forest cover (Lawrence et al., 2022). They are also irreplaceable for conserving tropical biodiversity, many specialized species are unable to recolonize secondary forests and rely on older, less altered, more structurally developed, and biodiverse habitats to persist in human-modified landscapes (Barlow et al., 2007).

The Atlantic forest has a large potential for natural regeneration and many conservation and restoration policies are in place (Scarano & Ceotto, 2015; Wilson et al., 2017). Restoring the existing legal debt of 5.2 Mha of riparian areas could increase native forest cover in Atlantic Forest by up to 35% (Rezende et al., 2018). The region presents a huge suitability for new approaches to ecological restoration, that can be achieved by land-use planning that seeks to diversify the types of restoration accepted (Resolução SMA 189, 2018). They can be strategically positioned in the landscape to maximize services, protect watersheds, erosion – prone zones, buffer zones alongside forest fragments to conserve biodiversity and protect from edge effects and degradation. If appropriately designed, incentivized, and enforced, these can drastically reduce the ongoing deforestation, conserve biodiversity, mitigate water and food insecurity, promote ecosystem-based mitigation and adaptation to climate change, and became a carbon source lansdcape.

5. **CONCLUSION**

The Atlantic forest has been experiencing a forest regeneration process observed in different regions (this study, Costa et al., 2017; Rezende et al., 2015; Rosa et al., 2021). Also the LULCC dynamics observed in this study, of the ongoing loss of old-growth native native forests are being covered by the increase of secondary native forest, has been happening widely in the Atlantic tropical forests (Costa et al., 2017; Rosa et al., 2021; Wilson et al., 2017).

By reconstructing the history of LULCC of this highly fragmented landscape, this study presents a unique data to understands the landscape carbon stock dynamics, including carbon stocks and flows, allowing us to realize the importance of protecting old-growth forest areas, and also estimate the potencial carbon sequestration if we allow the secondary native forest to achive maturity, and restore the existing legal debt of riparian areas.

The regeneration of the Atlantic forest, the climate change mitigation agreements and the demand for ecosystem goods and services, are an evidence that this is a decisive moment for the forest transition, the turning point of a history of degradation and loss, that can potentially turned into forest restoration and conservation future, and a carbon sink landscape.

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7. SUPPLEMENTARY MATERIALS

Table 1 - Land use and land cover transition matix 1985-2003 - hectares

1985 / 2003	Urban area	Eucalyptus	Secondary native forest	Old-growth native forest	Others	Pasture	Total 1985
Urban area	8589.81	0.00	1.32	0.00	5.85	4.37	8601.34
Eucalyptus	0.00	0.00	0.74	0.00	0.00	0.08	0.83
Old-growth native forest	360.72	5251.26	0.00	143512.12	1966.21	20918.23	172008.54
Others	375.75	155.89	1248.07	0.00	15265.20	5525.56	22570.48
Pasture	4413.08	2044.51	18277.89	0.00	28346.29	135321.86	188403.63
Total 2003	13739.36	7451.67	19528.02	143512.12	45583.55	161770.11	391584.82

Table 2 - Land use and land cover transition matix 2003-2020 - hectares

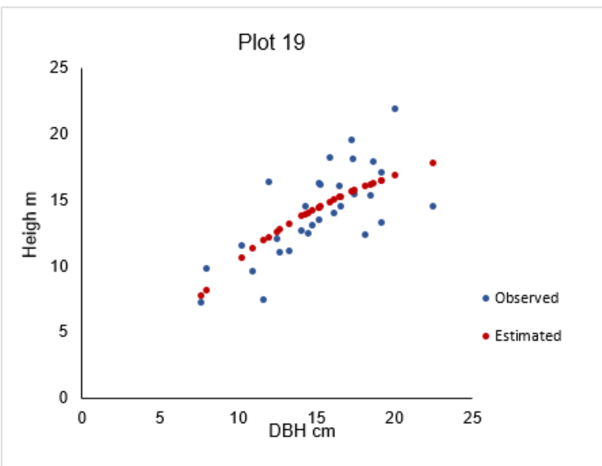
2003 / 2020	Urban area	Eucalyptus	Secondary native forest	Old-growth native forest	Others	Pasture	Total 2003
Urban area	13686.14		12.19	0.00	30.32	10.71	13739.36
Eucalyptus	3.13	6034.14	1088.81	0.00	131.78	193.80	7451.67
Secondary native forest	46.61	2010.32	9450.14	4915.79	705.74	2399.42	19528.02
Old-growth native forest	73.46	6942.39	0.00	130156.59	1388.55	4951.13	143512.12
Others	1428.50	632.91	1300.21	0.00	36390.90	5831.02	45583.55
Pasture	1378.65	8673.83	20361.59	0.00	32612.55	98743.49	161770.11
Total 2020	16616.49	24293.59	32212.95	135072.38	71259.85	112129.56	391584.82

Table 3 - Hypsometric models adjusted of plot 19 and 20

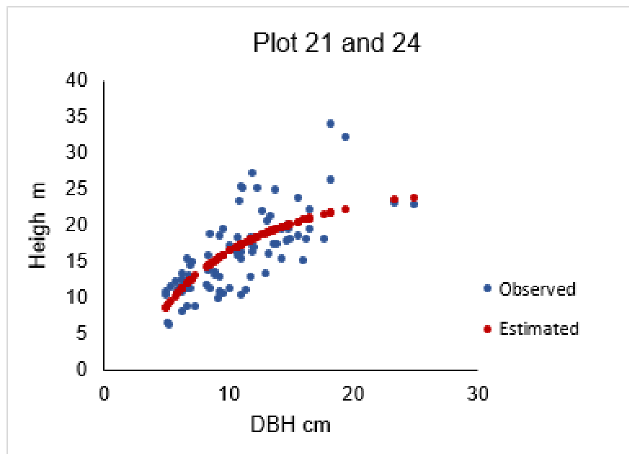
Model	B0	B1	B2	R^2 Ajusted %	Standart error %	F	Ajusted equation
Simple linear	3.62	0.68		48%	17%	27.458	H=3.6244 + (0.6854*DAP)
Parabolic (Trorey)	-4.56	1.86	-0.04	49%	17%	15.128	H=-4.5619 + (1.8623*DAP)+(-0.0400*DAP²)
Henricksen	-11.87	9.62		50%	17%	29.779	H=-11.8786 + 9.6272*LN(DAP)
Stofells	0.53	0.77		48%	13%	36.409	H=EXP((0.5344 + 0.7713*LN(DAP))* 1.0153)
Curtis	3.29	-9.73		50%	13%	36.448	H=EXP((3.2928 +(-9.7343*1/DAP))* 1.0153)

Table 4 - Hypsometric models adjusted of plot 21 and 24

Model	B0	B1	B2	R^2 ajustad %	Standart error %	F	Ajusted equation
Simple linear	5.74	0.95		52%	23%	98.58	H=5.742 + (0.953*DAP)
Parabolic (Trorey)	1.05	1.79	-0.03	53%	23%	49.66	H=1.057 + (1.793*DAP)+(-0.033*DAP²)
Henricksen	-8.66	10.68		53%	23%	98.58	H=-8.660 + 10.681*LN(DAP)
Stofells	1.13	0.68		52%	21%	115.65	H=EXP((1.138 + 0.684*LN(DAP))* 1.0242)
Curtis	3.40	-6.41		53%	21%	112.52	H=EXP((3.4018 + (-6.419)*1/DAP)* 1.0246))



a.



b.

Fig. 1. Adjusted hypsometric model: a - Curtis model for plot 19, b- Curtis model plot 21 and 24.

Table 5 – Carbon estimates on AGB by plot

	Typology	Plot_id	Carbono T ha⁻¹	CO² Mg ha⁻¹
1	Old-growth native forest	CAN_01	110.3	404.44
2	Old-growth native forest	CAN_02	127.35	466.95
3	Secondary native forest	CAN_03	92.04	337.48
4	Old-growth native forest	CAN_04	74.67	273.78
5	Secondary native forest	CAN_05	79.86	292.84
6	Secondary native forest	CAN_06	40.65	149.06
7	Secondary native forest	CAN_07	29.38	107.74
8	Old-growth native forest	CAN_08	132.58	486.12
9	Old-growth native forest	CAN_12	114.63	420.33
10	Pasture	CAN_14	1.57	5.75
11	Pasture	CAN_15	3.03	11.09
12	Pasture	CAN_16	2.51	9.2
13	Pasture	CAN_17	1.97	7.23
14	Pasture	CAN_18	3.63	13.3
15	Eucalyptus	CAN_19	5.87	21.51
16	Eucalyptus	CAN_20	5.87	21.51
17	Eucalyptus	CAN_21	5.59	20.48
18	Eucalyptus	CAN_22	8.41	30.8
19	Eucalyptus	CAN_23	8.81	32.25
20	Eucalyptus	CAN_24	8.78	32.14

Table 6 - Landscape Carbon Stock estimates of Eucalyptus plantation

Growing year	SisEucalipto Carbon Stock estimates CO_2 Mg ha⁻¹					
	CAN_19	CAN_20	CAN_21	CAN_22	CAN_23	CAN_24
1	0.2	0.2	0.2	0.3	0.3	0.3
2	4.3	4.3	3.9	6.8	7.2	4.3
3	14.5	14.5	13.4	21.6	22.7	14.5
4	28.3	28.3	26.8	41	43	28.3
5	43.7	43.7	41.8	62.2	65.1	43.7
6	59.6	59.6	57.3	83.7	87.5	134*
7**	0	0	0	0	0	0
Avarage CO_2 Mg	21.51	21.51	20.48	30.80	32.25	32.14
Plot Estimate (Soares & Oliveira, 2002)	39.53	39.53	29.91	84.99	128.83	101.09*

* added the carbon stock of the native species growing in the stand.
**Harvesting year, AGB loss.