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Forest restoration contribution to mitigating climate change: carbon storage as one of the main resources

Anani Morilha Zanini

Thesis presented to obtain the degree of Doctor in Science. Area: Forest Resource. Option in: Conservation of Natural Ecosystems

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Forest Engineering

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versão revisada de acordo com a Resolução CoPGr 6018 de 2011

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I dedicate this thesis to my dear parents:
Pedro Paulo and Viviane

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SUMMARY

RESUMO

Contribuições da restauração florestal na mitigação das mudanças climáticas: estoque de carbono como um dos principais recursos

A mudança no uso do solo, principalmente o desmatamento nas regiões tropicais, é a terceira maior fonte de emissões de gases do efeito estufa. As áreas em processo de restauração florestal são importantes ferramentas para a mitigação das mudanças climáticas, pois o sequestro do carbono decorre do crescimento das árvores e consequente acúmulo de biomassa. Assim, tornam-se necessários estudos que quantifiquem esses serviços ecossistêmicos considerando diferentes situações ambientais na paisagem. O objetivo geral deste trabalho foi estimar o potencial de provisão de serviços ecossistêmicos de regulação climática e ganhos financeiros com créditos de carbono em áreas em processo de restauração. O trabalho foi divido em três capítulos, sendo a primeira parte do estudo uma revisão bibliométrica sobre o processo de monitoramento de estoque de carbono em projetos de restauração florestal, a fim de detectar as tendências, os indicadores utilizados, as principais demandas e os desafios desses estudos. Na segunda parte foi investigado o potencial dos diferentes usos da terra para a mitigação das mudanças climáticas, através da quantificação do estoque de carbono em diferentes compartimentos em paisagens na Mata Atlântica. Por fim, o terceiro capítulo com cunho mais social e econômico visou estimar o ganho ambiental e financeiro que pode ser obtido pelo pagamento por serviço ambiental de sequestro de carbono na restauração florestal em Áreas de Preservação Permanente (APP) por proprietários rurais, o incentivo a valoração dessas áreas pode contribuir para a identificação de estratégias eficazes de restauração ambiental de APP e ao maior estímulo à adoção dessas medidas pelos proprietários rurais, com benefícios tanto para o meio ambiente quanto para a economia local. Os resultados dessa teses apresentam o estoque de carbono em restaurações florestais sob diversas caminhos, podendo ser utilizados para futuras pequisas científicas bem como em tomadas de decisão na formulação e implementação de políticas públicas, em consonância com estratéias globais de mitigação das mudanças climáticas.

Palavras-chave: Restauração ecológica, Serviços ecossistêmicos, Sequestro de carbono, Mercado de carbono, Mata Atlântica

ABSTRACT

Forest restoration contribuition to mitigating climate change: carbon storage as one of the main resources

Land use change, particularly deforestation in tropical regions, is the third largest source of greenhouse gas emissions. Areas in process of forest restoration are important tools for mitigating climate change, as carbon is sequestrated from tree growth and consequent accumulated in biomass. Thus, studies are needed to quantify these ecosystem services in ecological restorations, considering different environmental variations in the landscape. With this, the general objective of this work aims to estimate the potential for providing ecosystem services for climate regulation and financial gains from carbon credits in areas undergoing restoration. This study was divided into three chapters, the first, is a literature review carried out on how carbon storage monitoring in forest restorations occurs, in order to detect trends, indicators used, and the main demands and challenges of the studies. In the second part, the potential of different land uses to mitigate climate change was investigated, through the quantification of the carbon stock in different compartments in landscapes in the Atlantic Forest. Finally, the third chapter, with a more social and economic nature, aimed to estimate the environmental and financial gain that can be obtained by paying landowners for the environmental service of carbon sequestration in forest restoration in Permanent Preservation Areas (PPA). It may contribute to the identification of effective strategies for environmental restoration of PPA and to encourage the adoption of these measures by rural landowners, with benefits both for the environment and for the local economy. The results of these theses present the carbon stock in forest restorations under different paths, and can be used for future scientific research as well as in decision-making in the formulation and implementation of public policies, in line with global strategies for mitigating climate change.

Keywords: Ecological restoration, Carbon sequestration, Ecosystem service, Carbon market, Atlantic Forest

1. INTRODUTION

It is estimated that one-third of the world's population is directly affected by environmental degradation (Ghazoul et al., 2015; Olsson et al., 2019). Part of this degradation is associated to change land use, which result in a loss of US$ 4.3 to 20, 2 billion per year (Constanza et al., 2014). In the tropical region, characterized as being the most complex and biodiverse terrestrial ecosystem on the planet (Malhi et al. 2014), the total area of degraded forest is around 500 million hectares (Putz & Romero, 2014), which causes fragmentation and depreciation of areas.

Environmental degradation contributes negatively to global climate change, since, in addition to increase in carbon emissions, deforestation has reduced the number of forest areas and the consequent carbon sequestration, which is carried out mostly by trees (IPCC, 2023). In addition, the photosynthetic process and respiration carried out by plants contribute to the cycling of water and carbon, providing numerous ecosystem services (Crowther et al., 2015). In this scenario, ecosystem services, which are the fundamental benefits generated by ecosystems and directly affect human life quality, are being threatened by ecological imbalance and the consequent greenhouse gases concentration increase (Sukhdev, 2008; IPCC, 2021).

Ecosystem services can be classified into four groups: i. Provisioning services, which includes goods or products obtained from ecosystems, such as water, food, and wood; ii. Support services, which are those services necessary for the production of other ecosystem services and help maintain life on Earth, such as nutrient cycling, pollination and biodiversity conservation; iii. Regulatory services, that relates to the regulatory characteristics of ecosystem processes, such as maintaining air quality, climate regulation and erosion control; vi. Cultural services, that consists of non-material benefits and with more educational and aesthetic values, for example recreation, tourism, cultural identity and knowledge passed over generation (MEA, 2005).

Carbon sequestration and storage are essential ecosystem services for climate regulation. The carbon fixed by forests is stored in different forest compartments. Thus, biomass estimates are crucial for studies on climate change (Brown, 1997), making it possible to assume how much carbon is stored by area, and the impact of silvicultural treatments on forest growth. However, most works that quantify the carbon stock in secondary forests consider only aboveground living biomass (Poorter et al., 2016) or only soil organic matter, that is the organic component of soil and represents the largest terrestrial carbon pool (Don et al., 2011), rarely including, other forest compartments (Anderson-Teixeira et al., 2016), such as belowground biomass and dead organic matter (Birdsey et al., 2000).

Therefore, considering carbon stocks above and below ground in different compartments is essential to understand how carbon accumulation of the forest occurs (Chazdon et al., 2016; Powers and Marín-Spiotta, 2017; Zanini et al., 2021). Another point to consider is that there is no pattern between carbon stock and the age of areas (Estrada & Soares, 2017). Although there is a tendency for aboveground biomass to increase with succession, different studies report increases, decreases, and unchanged soil carbon at similar time scales (Powers & Marín-Spiotta, 2017).

Tropical forests are particularly important in the global carbon balance, as they account for approximately 40% of the global terrestrial carbon sink (Malhi, 2010) around 55% of the global aboveground carbon stock (Pan et al., 2011). Considering this importance, there has been an increase in large-scale forest restoration projects, on carbon markets and on the pressure to reduce the emission of greenhouse gases to the atmosphere (Gardon et al., 2020). The first agreement reached was the Kyoto Protocol in 1997, however, only developed countries participated (UNFCCC, 2007). With this in 2015, a new international treaty, the Paris Agreement, was created, involved 195 nations and aimed for greater cooperation in achieving more effective and appropriate goals (UNFCCC, 2015). One of the main one is the Bonn Challenge is a global goal to restore 350 million hectares of degraded and deforested landscapes by 2030 (IUCN, 2015; Chazdon et al., 2017).

Since 1972, the United Nations (UN) has held global meetings in which political leaders from different countries recognize that anthropic activities can negatively impact the environment and contribute to climate change worsening. In these meetings, possible solutions are discussed to revert the causes of this problem, establishing targets to reduce concerning the emission and mitigation of GHGs. Since 2005, with the ratification of the Kyoto Protocol, the fulfillment of these goals is subject to the generation of carbon credits and commercialization in the regulated carbon market.

According to Lamb (2014), ecological restoration aims to restore environmental functionality of areas and improve human well-being. International commitments to restore the forest landscape have accumulated promises to restore more than 160 million hectares (Chazdon et al. 2017, Holl 2017), and may be the key to improving the planet's environmental conditions, so that expectations around the success of these actions are high, as the United Nations has declared the period from 2021 to 2030 as the decade of restoration.

Forest restoration can have different objectives and outcomes, depending on the stakeholders (Brancalion et al., 2015). When it comes to small landowners and communities, restoration can provide direct environmental improvements in food, water and energy productivity, to promote sources of income and ecosystem services. For companies, restoration is mainly used as compensation for environmental impacts caused by their activities or legal requirements (Chazdon et al., 2017). In this sense, that it is cheaper and more sustainable for companies to use terrestrial ecosystems than to invest in artificial installations and carbon sequestration technologies, attracting more attention to payment strategies for reducing emissions (Sapkota & White, 2020).

Taking into account the arguments presented and the importance of studies to combat global climate change, the objective of our work was to answer questions related to the carbon stock in forest restoration, as well as to the general objective of this work aims to estimate the potential for providing ecosystem services for climate regulation and financial gains from carbon credits in areas undergoing restoration. For this, the work will be divided into three chapters:

i. A bibliometric review in which the objective is to provide an overview of the carbon stock monitoring process in forest restoration projects stratified in the main areas of interest: i) where the studies were developed and published; ii) restoration methodologies and age of assessed areas; iii) the main monitoring indicators by biome; iv) knowledge gaps.

ii. Field research in which the potential of different land uses to mitigate climate change was investigated, to quantify the carbon stock in landscapes with different land uses in the Atlantic Forest, comparing the carbon stocks between the carbon compartments. Thus, the potential and contributions of different forest landscapes for carbon storage and the relationship between forest structure and total stock were evaluated.

iii. A socioeconomic study in which the objective was to estimate the environmental and financial gain that can be obtained from the payment for environmental service of carbon storage through forest restoration of Permanent Preservation Areas (APP) by landowners. It contributed to identify effective strategies for the environmental restoration of APPs and to encourage the adoption of these actions by landowners, with benefits for both the environment and the local economy.

The last chapter is a final consideration on the results found and the main topics addressed, with considerations for public policies the importance of conserving forests and encouraging the restoration of new areas to meet global climate goals, and consequent climate change mitigation.

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2. CARBON STOCK IN FOREST RESTORATION: A REVIEW

Abstract

Forest restoration is a highly effective strategy in combating climate change due to its potential to convert areas into large-scale carbon sinks. Our study aimed to evaluate the scientific literature focused on carbon stock in forest restoration areas worldwide. We assessed the age of the restoration area, the country in which the restoration took place, the journal publishing the research, the year of publication, and the restoration method employed by biome, as well as the importance of studying various forest compartments and identifying research gaps and trends in the field. Our literature review relied on four bibliographic sources and resulted in a database of 107 articles. The studies covered 26 countries and seven biomes and were published from 2003 to 2022, peaking in 2020. The project age ranged from six months to over 100 years, and the active forest restoration method was the most commonly applied, followed by the passive method. One only paper compared the active, the passive methods and the assisted methods. Additionally, we found that 31 studies assessed all the different forest compartments for carbon stock, while the remaining studies evaluated up to two pools only, which could bias carbon stock estimates. By examining the methodology by biome, we were able to identify patterns regarding the most common ways to restore areas based on region, which could guide researchers and decision-makers on identifying the most likely methods to succeed in each case. One noted a difference in the number of studies per region, and many areas around the world lack carbon stock monitoring. The failure to evaluate all forest compartments in studies may lead to possible underestimation of carbon, and different sampling methods for each type of biome should be taken into account to enable more precise calculation and comparison of data with other studies.

Keywords: 1. Biomass 2. Carbon Stock 3. Climate Change 4. Ecological Restoration 5. Peer-review

2.1. Introduction

Forests play a crucial role as CO_2 sinks (Crowther et al., 2015), functioning as one of the main tools to mitigate climate change (Seddon et al., 2019). This is one of the reasons why global agreements aiming to restore degraded areas have been made. For example, The Bonn Challenge aims to restore 350 million hectares of forest worldwide by 2030 (IUCN, 2015; Dave et al., 2017). In Canada, the two Billion Tree Commitment was set to be accomplished in ten years (Government of Canada, 2023). Brazil's Atlantic Forest Restoration Pact aims to recover 15 million hectares by 2050 (Rodrigues, Brancalion & Isernhagen, 2009). Achieving these ambitious goals is a challenge for the ecological restoration practice (Mayfield, 2016), in terms of scale, implementing of the forests, monitoring the succession (Brancalion & Holl, 2015), and ensuring that ecological function, biodiversity and services are being properly re-established.

Re-establishing an area back to mature forest is a complex task, because of the complexity ofits original biodiversity, ecosystem services and ecological functions (Toma et al, 2023), which challenges our current understanding of forest restoration (Rose and Marques, 2022). Besides restoring biodiversity, ecosystem services and ecological function, restoration projects need to behave as efficient carbon sinks to mitigate climate change. Thankfully, ecosystem functions, biodiversity and ecosystem services are correlated to productivity (Rosa and Marques, 2022). Therefore, monitoring carbon stock at restoration sites is a proxy to monitor how the restoration project is progressing regarding biodiversity, functions, and services and how much the area is mitigating global warming.

Thus, monitoring carbon stocks helps us understand natural processes for establishment (Zhu et al., 2017). Besides, monitoring carbon stock is essential in trading credits in the carbon market (van der Gaast et al., 2018), where biased estimates have financial consequences. More than financial consequences, biased estimates can jeopardize global mitigation strategies, as recently discussed on the media by The Guardian, Verra and others (Greenfield, 2023; Verra, 2023).

The main bias on carbon stock estimates is related to using inappropriate allometric equations (Gardon et al., 2020) and to not quantifying carbon in all forest pools (Zanini, et al, 2021). Although carbon stock monitoring is widely discussed across the globe nowadays, there are knowledge gaps in the forest restoration discipline to be addressed. Other literature reviews have been made, evaluating the science of forest restoration and carbon storage, but not on a global scale. Wortley, et al (2013) determined trends in restoration projects assessment regarding country and publication year, and identified a gap to be addressed to study social aspects of restoration. Aronson et al. (2010) focused on the social aspect of restoration sites. Our study diverges and complement theirs by focusing on monitoring carbon on the restoration sites. The objective of this peer-reviewed literature search is to provide an overview of the carbon stock monitoring process in forest restoration projects stratified into the main areas of interest: i) where the studies were developed and published; ii) the restoration methodologies applied and age of the evaluated areas; iii) the main monitoring indicators according to biome, and; iv) knowledge gaps.

2.2. Materials and Methods

2.2.1 Terminology

Restoration ecology is the scientific field that supports ecological restoration practices (Arodotti and Hagen, 2013; Romanelli et al., 2018), which is defined as the actions assisting the recovery of degraded, damaged or destroyed ecosystems (SER, 2004). Even though they have different meanings, in some exceptions, the term forest restoration and ecological restoration are widely used in academia to describe restoration projects (Brancalion et al., 2015). Therefore, the terms ecological restoration, restoration ecology, and forest restoration, combined with carbon stock are used in this study. We constrained our study to forest ecosystems, as forests cover almost one third of the planet’s area (Aerts & Honnay, 2011), and are estimated to stock up to 80% of terrestrial carbon (Houghton, 2008). The term "carbon stock" was opted for over "carbon sequestration" since it specifically pertains to the accumulation of carbon within biomass, rather than the broader process of extracting carbon from the atmosphere and storing it. This choice was influenced by the definition provided by Nowak and Crane (2002).

2.2.2 Data collection

We conducted a literature search using the following bibliographic sources: Web of Science (main collection: SCI-E, SSCI and ESCI), Scopus, CAB Direct, and SciELO. We searched these bibliographic sources with no restriction on the year of publication, combining the terms ("restoration ecology*" OR "ecological restoration*" OR "forest restoration*") AND ("carbon storage*" OR "carbon stock*").

Only studies meeting the following criteria were included: i) population: forest ecosystems; ii) restoring methodology: active, passive, or assisted forest restoration; iii) benchmark: reference forest areas (i.e., least disturbed forest areas in the region), or other land uses; iv) outcomes: carbon stock dynamics monitoring.

As we recognize that the process of choosing papers to assess can potentially be subjective (inclusion-exclusion decisions) (CEE 2018), a set of 20 articles deemed critically relevant to the data set were compared using the Cohen's kappa coefficient (Landis and Koch, 1977) to ensure the repeatability of inclusion and exclusion decisions. A Kappa score of 0.76 was obtained by two other searches, indicating substantial agreement between the reviewers and that the decisions are sufficiently repeatable (Appendix A).

Data were retrieved on September 18, 2021, resulting in a database of 1014 papers (Appendix B). These papers were analyzed for coverage and overlapping sources of information, resulting in 678 papers (Appendix C), which were screened for inclusion criteria using their titles, abstracts, and keywords. A list is provided with examples of excluded papers at this stage and the explanation for exclusion (Appendix D). A total of 107 papers remained for analysis (Appendix H).

2.2.3 Data analysis

The selected papers were investigated regarding its: i) Bibliometric indicators: identification of the first year of publication on the subject; the year with most publications; journals in which the studies were published; ii) Restoration characteristics: locations and biomes where the studies were performed; restoration methodologies applied (active forest restoration planting, or passive restoration (i.e. regrowth of the forest after land abandonment or cessation of disturbance pressure) or assisted restoration (driving the species of interest, controlling unwanted species, and planting tree species)); how the methods were compared; previous land use; age of restorations; iii) Monitoring protocol: carbon stock measurement methodologies (direct or destructive method) or indirect (modeling); the compartments in which the carbon stock was quantified (i.e. living biomass: aboveground (separated into strata: arboreal (bark, trunks, branches, leaves), shrub, and herbaceous) and belowground (separated into strata: fine and coarse root); dead biomass: litter, fallen and standing dead wood; and the soil organic matter at different depths).

The final data were analyzed in the spreadsheet tool Excel. We used descriptive statistics (median, mode, and mean) to enable comparison and VOSviewer software (version 1.16.15) to examine trends across the included studies. The software Biomeviewer was used to characterize the biome where each work was inserted, using the coordinates provided in the studies. The geographical locations of field studies were extracted and mapped by ArcGIS 10.2.

2.3. Results

2.3.1 Bibliometric Indicators

We analyzed 107 articles published in 55 peer-reviewed journals (Appendix E). From total, 32.71% of journals published one paper, 14.95% published two papers used in this study and 19.62% published three papers. The most relevant journal in the number of publications was Forest Ecology and Management, followed by Restoration Ecology, Ecological Engineering, Catena, and Ecological Application, which published 13.1%, 6.5%, 5.6%, 3.7%, and 3.7% of the papers considered in this study, respectively. The first study about carbon stock monitoring in restoration areas was published in 2003, and most publications occurred after 2011 (90.65%), with the year 2020 having the highest number of publications (15.88%). More information about the studies is in the supplementary material.

2.3.2 Restoration characteristics

The articles were performed in 26 countries (Figure 1; Appendice F). China was the country publishing the highest number of studies (40.18%), followed by the United States (14.01%), Brazil (8.41%), India (5.61%), Russia (3.73%), South Africa (2.80%), Australia (2.80%), and Ethiopia (2.80%). In terms of biomes, most studies assessed areas in Temperate Deciduous Forest (42.05%), followed by Tropical Rain Forest (31.77%), Temperate Coniferous Forest (10.28%), Tropical Dry Forest (8.41%), Boreal Forest (3.72%), Chaparral (2.80%), and Desert (0.93%) (Appendix G). Although desert, boreal and chaparral biomes are not forests, the areas in the studies assessed were restored using forest restoration techniques, therefore, they were considered for this analysis.

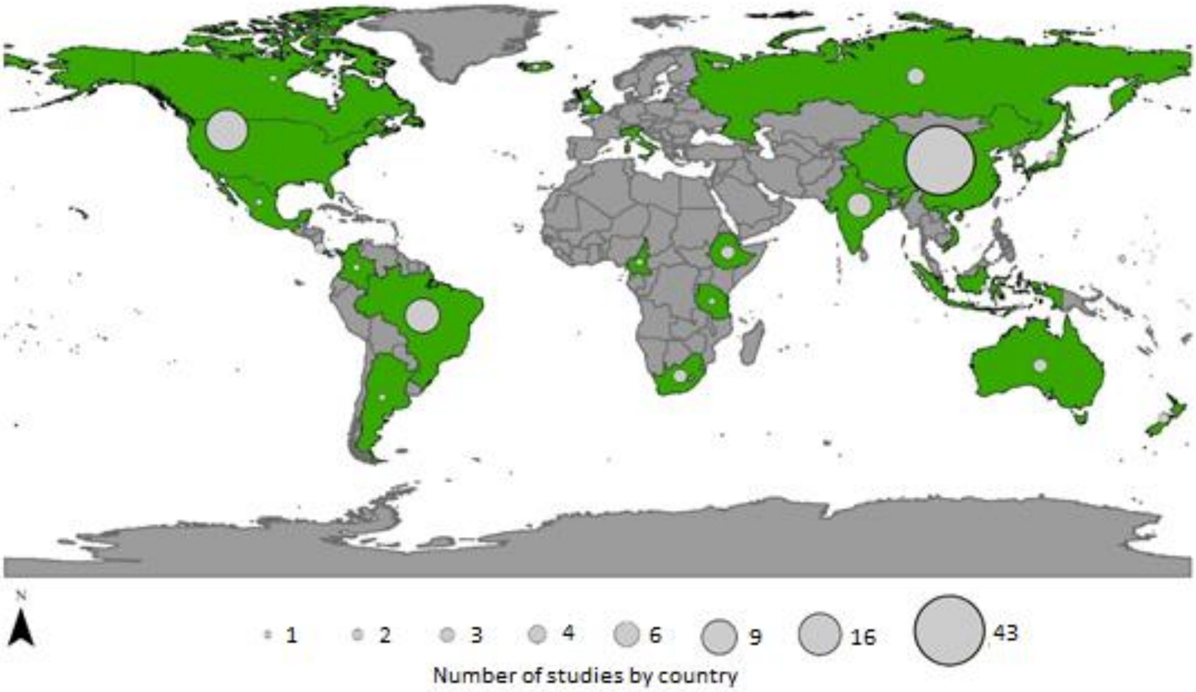

Figure 1. Number of studies by country assessing carbon stock in forest restoration areas. Countries highlighted in green had studies being performed. The circles size is proportional to the number of publications per country assessed in this review.

All restoration projects on the papers analyzed were performed to replace different land uses. Agriculture (43.93%) was the main cause of conversion, followed by degraded forest (19.63%), pasture (17.76%), mining areas (4.67%), farming (3.74%), urbanized areas (2.80%), and others (7.45%). In the studies applying the active restoration technique, almost all areas were implemented by planting seedlings (80%), direct seeding was found in three studies, nucleation and geojute were found in one study.

The active restoration was the most evaluated method among the studies, with a total of 78 studies, followed by the passive method with 54, and assisted with one study. Of these studies, 53 studies evaluated only active restorations, and 29 only passive restorations. In total, 24 papers evaluated and/or compared the active and passive implementation methodologies, and one study compared the passive, active and assisted methods (Figure 2). Age of the restoration sites at assessment ranged from zero to 100 years from implementation. Many publications (74%) assessed the same area at least twice, which allowed to illustrate the influence of age on carbon storage. For the active methodology, most studies evaluated the area 30 years after implementation although assessment after 71 years of implementation were recorded. For the passive restoration, the oldest site is 100-year old (Figure 3). The study that compared the three methodologies were five years old at assessment.

Figure 2. Restoration methodologies performed in the studies analyzed.

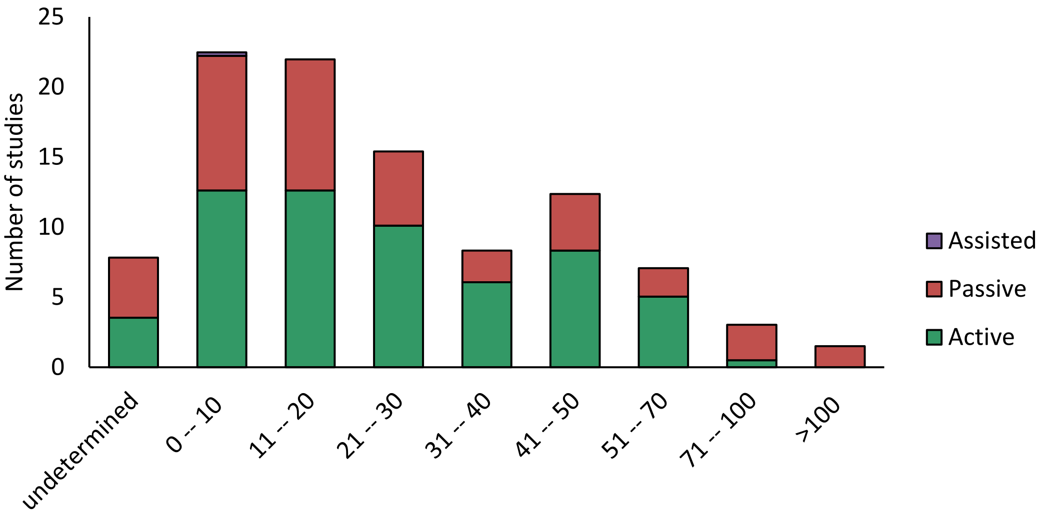

Figure 3. Restoration methodologies (active; passive; assisted) and age class at assessment.

2.3.3 Monitoring protocol

The soil was the most evaluated pool (82.24%), followed by living biomass (59.81%) and dead organic matter (35.51%). From all studies assessed, 31 studies evaluated the three compartments, 21 studies considered two (living biomass and dead organic matter), and 55% only evaluated one compartment (Figure 4). Stratifying the living biomass pools, the tree stratum was the most studied compartiment, assessed by 62 papers, followed by herbaceous, coarse root, fine roots and shrubs, assessed by 35, 29, 27, and 25 papers, respectively. Stratifying dead biomass, litter was the most studied pool with 36, followed by dead wood with 16 (Figure 5).

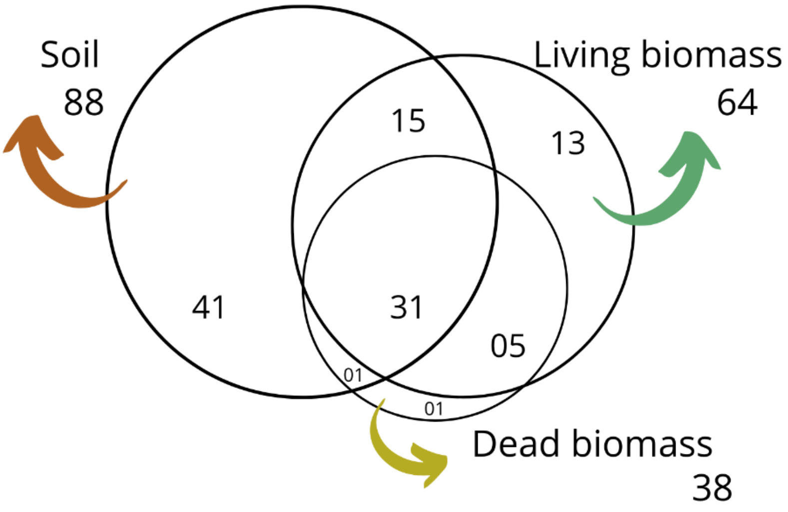

Figure 4. Compartments where carbon stocks were quantified in the studies analyzed.

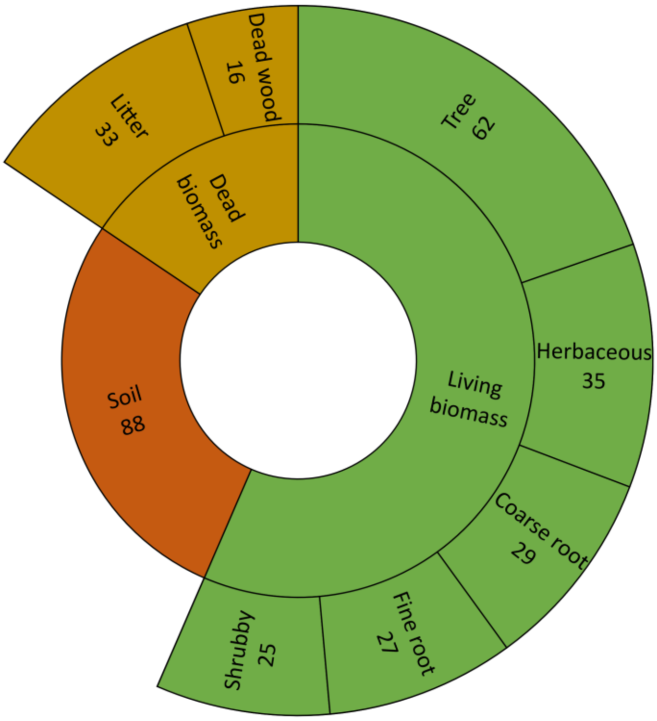

Figure 5. Compartments (Living Biomass; Dead Biomass; Soil) and stratum (Trees; Coarse Roots; Herbaceous; Shrubs; Fine Roots; Litter; Dead Wood) in which the carbon stocks were evaluated and quantified in the studies analyzed.

Ways of measuring carbon stock in different biomes were assessed in this study to facilitate the understanding of the different methodologies according to the environment towards a better comparison of the methods. Table 1 presents the methodologies used to assess carbon in the studies analyzed, divided into: direct or indirect, for the different compartments (Living Biomass, Dead Biomass, Soil), and forest strata (Trees, Shrubs, Herbaceous, Thick Root, Thin Root, Ground Wood, Dead Wood) by biome. In the desert, where only one study was carried out, carbon stock was assessed in the soil up 20 cm. For Chaparral and Boreal Forest, as few studies were performed, we could not define a trend in the methodology used. The lack of studies in these regions, makes it impossible to draw more conclusions about the method used the most, or the most appropriated method.

In the tropical biomes, soil was the most evaluated compartment, assessed in the 0 - 30 cm layer. In the temperate biome, soil was assessed up to the 100 cm depth in most cases. The tree stratum was the second most assessed forest compartment. Chronosequences were used in 25.81% to direct estimate carbon stock. Most studies applied indirect methodologies. Among them, four studies (6.45%) used Geographic Information Systems (GIS) to estimate forest biomass and then apply an indirect and/or reference value. This work has been done in the Temperate Deciduous and Tropical Rainy biomes. Most studies, however, used allometric (30.65%) or volumetric (37.1%) equations to estimate biomass, and only the indirect methodology through volumetric equations could cover all the biomes presented here: Boreal, Chaparral, Temperate and Tropical. To estimate the shrub, herbaceous, fine-root and litter layers, the direct collection methodology was predominant, starting with the sampling of different measured areas or soil depths.

Regarding the estimates of carbon content, in the studies where direct sampling of the compartments was carried out, the analysis of carbon content was subsequently performed. For those where indirect estimation was performed, indirect and/or reference carbon content values were also used, with 64%, 21% and 10% of the studies considering 0.50, 0.47 and 0.48 as reference values for carbon content, respectively.

Table 1. Studies in percentage, the different methodologies and measurement forms used for monitoring carbon stocks among the different compartments (soil organic matter, living biomass, dead organic matter) and strata (soil, tree, shrub, herbaceous, coarse root, fine root, litter, dead wood), regarding the different biomes (Desert, Chaparral, Boreal, Dry Tropical Forest, Temperate Conifer Forest, Rain Tropical Forest, Deciduous Temperate Forest).

Desert (n=1)

Compartment	Stratum	Method	How	Studies (%)
Soil	Soil	Direct	20 cm collection depth	100.00

Chaparral (n=3)

Compartment	Stratum	Method	How	Studies (%)
Soil	Soil	Direct	30 cm collection depth	33.33
			60 cm collection depth	33.33
			100 cm collection depth	33.33
Living biomass	Tree	Indirect	Forest inventory; Use of Allometric Equation	50.00
			Forest inventory; Use of Expansion Factor	50.00
	Shrub	Direct	20 m² collection area	100.00
	Herbaceous	Direct	4 m² collection area	100.00
	Coarse root	Indirect	Forest inventory; Use of Allometric Equation	100.00
	Fine root	Direct	30 cm collection depth	50.00
			100 cm collection depth	50.00
Dead biomass	Litter	Direct	0.09 m² collection area	50.00
			4 m² collection área	50.00

Boreal Forest (n=4)

Compartment	Stratum	Method	How	Studies (%)
Soil	Soil	Direct	30 cm collection depth	66.67
			10 cm collection depth	33.33
Living biomass	Tree	Indirect	Forest inventory; Use of Allometric Equation	100.00
	Herbaceous	Direct	0.0625 m² collection area	50.00
			0.25 m² collection area	50.00
	Fine root	Direct	30 cm collection depth	100.00

Dead biomass	Dead wood	Indirect	Interception line	100.00
Tropical Dry Forest (n=9)				
Compartment	**Stratum**	**Method**	**How**	**Studies (%)**
Soil	Soil	Direct	5 cm collection depth	14.29
			10 cm collection depth	14.29
			30 cm collection depth	28.57
			60 cm collection depth	14.29
			100 cm collection depth	14.29
		Indirect	Simulation model LANDIS-II	14.29
Living biomass	Tree	Direct	Forest inventory; Tree Cubing; Dry Weight of Individuals	33.33
		Indirect	Forest inventory; Use of Allometric Equation	50.00
			Simulation model LANDIS-II	16.67
	Herbaceous	Direct	0.5 m² collection area	100.00
	Coarse root	Direct	Forest inventory; Tree Cubing; Dry Weight of roots	25.00
		Indirect	Forest inventory; Use of Allometric Equation	50.00
			Allometric relation of Tree x Root	25.00
Dead biomass	Litter	Direct	2 m² collection area	100.00
	Dead wood	Indirect	Simulation model LANDIS-II	100.00
Temperate Conifer Forest (n=11)				
Compartment	**Stratum**	**Method**	**How**	**Studies (%)**
Soil	Soil	Direct	10 cm collection depth	20.00
			30 cm collection depth	60.00
			80 cm collection depth	20.00
Living biomass	Tree	Direct	Forest inventory; Tree Cubing; Dry Weight of Individuals	11.11
		Indirect	Forest inventory; Use of Allometric Equation	88.89
	Shrub	Direct	4 m² collection area	50.00
		Indirect	Forest inventory; Percentutal Cover; Use of Allometric Equation	50.00
	Herbaceous	Direct	1 m² collection area	100.00
	Coarse root	Indirect	Forest inventory; Use of Allometric Equation	100.00

	Fine root	Direct	30 cm collection depth	50.00
			Hydropneumatic Elutriation System	50.00
Dead biomass	Litter	Direct	1 m^2 collection area	66.67
			0.159 m^2 collection area	33.33
	Dead wood	Direct	Brown Method (1974)	40.00
			25 m^2 collection area	20.00
		Indirect	Forest inventory; Use of Allometric Equation	40.00
Tropical Rain Forest (n=35)				
Compartment	**Stratum**	**Method**	**How**	**Studies (%)**
Soil	Soil	Direct	10 cm collection depth	4.00
			15 cm collection depth	4.00
			20 cm collection depth	24.00
			30 cm collection depth	28.00
			40 cm collection depth	4.00
			50 cm collection depth	4.00
			60 cm collection depth	4.00
			90 cm collection depth	4.00
			100 cm collection depth	24.00
Living biomass	Tree	Direct	Forest inventory; Tree Cubing; Develop of alometric Equation	8.70
			Forest inventory; Tree Cubing; Dry Weight of Individuals	17.39
		Indirect	Forest inventory; Use of Allometric Equation	69.57
			Remote Sensoring	4.35
	Shrub	Direct	1 m^2 collection area	20.00
			4 m^2 collection area	60.00
			Sampling of 3 individuals	20.00
		Indirect	Forest inventory; Use of Allometric Equation	66.67
			Abundance Indicator	33.33
	Herbaceo	Direct	0,0625 m^2 collection area	14.29
			1 m^2 collection area	57.14
			4 m^2 collection area	14.29
			8 m^2 collection area	14.29
	Coarse root	Direct	Forest inventory; Tree Cubing	100.00

		Indirect	Allometric relation of Tree x Root	50.00
			Forest inventory; Use of Allometric Equation	50.00
	Fine root	Direct	10 cm collection depth	60.00
			30 cm collection depth	20.00
			100 cm collection depth	20.00
Dead biomass	Litter	Direct	0.0625 m^2 collection area	16.67
			0,25 m^2 collection area	25.00
			1 m^2 collection area	50.00
			2 m^2 collection area	8.33
	Dead wood	Direct	25 m^2 collection area	100.00
		Indirect	Forest inventory; Use of Allometric Equation	50.00
			Interception line	50.00
Temperate Decidual Forest (n=46)				
Compartment	**Stratum**	**Method**	**How**	**Studies (%)**
Soil	Soil	Direct	10 cm collection depth	12.82
			15 cm collection depth	10.26
			16 cm collection depth	2.56
			19 cm collection depth	2.56
			20 cm collection depth	12.82
			30 cm collection depth	2.56
			50 cm collection depth	5.13
			60 cm collection depth	2.56
			80 cm collection depth	2.56
			100 cm collection depth	38.46
			200 cm collection depth	2.56
			300 cm collection depth	2.56
			400 cm collection depth	2.56
Living biomass	Tree	Direct	1 m^2 collection area	14.29
			Forest inventory; Tree Cubing; Develop of Alometric Equation	28.57
			Forest inventory; Tree Cubing; Dry Weight of Individuals	57.14
		Indirect	Forest inventory; Use of Allometric Equation	92.86
			Remote Sensoring	7.14

	Shrub	Direct	4 m^2 collection area	40.00
			25 m^2 collection area	60.00
		Indirect	Forest inventory; Use of Allometric Equation	100.00
	Herbáceo	Direct	0.25 m^2 collection area	9.09
			1 m^2 collection area	81.82
			4 m^2 collection area	9.09
	Coarse root	Direct	100 cm collection depth	28.57
			Forest inventory; Tree Cubing;	71.43
		Indirect	Allometric relation of Tree x Root	33.33
			Forest inventory; Use of Allometric Equation	66.67
	Fine root	Direct	40 cm collection depth	20.00
			100 cm collection depth	80.00
Dead biomass	Litter	Direct	0.04 m^2 collection area	9.09
			0.25 m^2 collection area	45.45
			1 m^2 collection area	36.36
			25 m^2 collection area	9.09
		Indirect	Interception line	100.00
	Dead wood	Indirect	Interception line	100.00

2.4. Discussion

In this review, it was possible to identify the studies that evaluated the carbon stock in several areas in of forest restoration areas around the world, finding the main methodologies, trends and gaps in this monitoring.

China and the United States are countries where most research in ecological restoration (Romanelli et al., 2018), and carbon stock monitoring in restored areas were performed. Wortley et al (2013) in a review about restoration science back in 2013 found that the United States was the country where most published studies took place, and attributed it to economic causes. It highlighting the importance of increasing studies in all regions to better understand the restoration process in each situation, and to improve conservation and restoration policies (Silveira et al., 2021). Likewise, Gardon et al (2020) assessing the knowledge gap in Brazil´s forest restoration and carbon stock found out that most studies were focused on the Atlantic forest, not equally distributed in all Brazilian biomes.

Restoration ecology is a young science (Martin, 2017). Started in the 1980s (Rodrigues et al., 2009) and more studies were added over the years at increasing rate (Romanelli et al., 2018). The relevance and increasing discussion in the restoration science in recent years may be related to the increasing rate of the global climate change crisis and mitigation initiatives and commitments that have been launched in recent decades (Dave et al., 2017). Conversion from agriculture to forest was pointed out by Deng et al. (2016) as one of the highest increases in carbon soil stock after a conversion. Prior land use affects the priority given for an area be restored (Leal et al., 2019), the methodology applied, the silvicultural treatments prescribed and the probability of success of restoration (Crouzeilles et al., 2016). Consequently, prior land use affects carbon stockage in the restoration after conversion. Therefore, previous land use is an important factor to be considered in the forest restoration project specially when choosing the restoration method applied (Coutinho et al., 2010; Liu et al., 2018).

From all studies assessed, the active restoration, which is a strategy that accelerates the ecological succession process through actively planting seedlings in the area (Vaughn et al., 2010), was the most used method, followed by the passive restoration, in which natural succession is supported and unfavorable factors are suppressed, reduced, or eliminated in some extend (Vaughn et al., 2010). The assisted restoration, which uses driving techniques stimulating the species of interest, suppressing the unwanted, along with seedling planting (Rodrigues et al., 2009; Brancalion et al., 2016), was found in one study (0.93%). In the active method, biodiversity and carbon stock tend to increase more efficiently by actively increasing individuals at the site, which is linked to ecosystem functions (productivity, soil stability and nutrient cycling) and ecosystem services (soil fertility, erosion control, water supply, pests and pathogen regulation).

Almost all areas in the studies assessed were implemented by planting seedlings. Direct seeding, less efficient but cheaper compared to planting seedlings (Freitas et al., 2019). Gardon (2020) also found that seeding was less used than seedlings to restore Brazilian´s forest ecosystems. Other methodologies found, but on a smaller scale compared to plantations, were nucleation, a method in which restoration techniques are applied in nucleus, not in total area, accelerating the natural succession processes (Reis et al., 2014), and the geojute technique, which is used to reestablish mountainous ecosystems after and to prevent landslides (Mehta et al., 2018). This lack of studies using different restoration methods evidences one important bottleneck restoration science faces. It is crucial to test and compare different methods in different biomes, previous land use, and situations. Even when using the active method, the most studied one, the best silvicultural treatments applied are not a consensus in most studies. The active method is used beyond the phase of implementation. It is also used to restore forest structure, for example thinning, and prescribed fire (McCauley et al., 2019). Studies comparing methodologies in the same area are critical to elucidate the effectiveness and differences between the strategies (Atkinson & Bonser, 2020; Crouzeilles et al., 2017). One single study compared the passive, active and assisted methods (Zanini et al. 2021).

To increase the understanding of carbon dynamics in forests, and increasing modeling precision, the use of other forest compartments is crucial in carbon stock assessments (Zanini et al., 2021). Terrestrial ecosystems are considered to be major carbon sinks, especially soils (Machado, 2005). Studies show that global soil carbon stocks range from 700 to 2946 Pg C in one-meter depth (O'Rourke et al., 2015), very significant stock for climate change mitigation. Besides, soils may be the main source of emissions after deforestation (Page et al., 1997). Therefore, to monitor soil carbon stock is fundamental to make sure that the restoration project successfully reverted the process of behaving as a source to sink.

Reviewing global soil carbon stocks, Li et al. (2012) indicated that restoring forests indeed increases total soil carbon stocks. However, carbon stock in the soil is highly variable in terms of depth, method of extraction, and if it was sampled from organic or mineral layers (Coutinho et al., 2010; Liu et al., 2018). The top (or organic) soil layer generally has the highest carbon content in forest soils (Li et al., 2012). In fact, this is the most studied layer: 50.59% of the studies analyzed here measured soil carbon content up to the 30 cm layer. The other half (49.41%) concentrated measurements between the depths of 40 to 100 cm.

Aboveground biomass is being accounted by a higher number of researches over the years (Petrokofsky et al., 2012) compared to belowground biomass. In addition, biomass estimation by forest inventory is one of the most common methods of measurement (Fang et al., 1998). On the other hand, belowground estimates are rare, due to the difficulties of the excavation process, measurement, and cost, although important in the carbon cycle (Eggleston et al., 2006). Although the living biomass and soil have been the focus of most research, dead wood and liter can stock large amounts of carbon as living biomass (Petrokofsy et al., 2012). Besides, other pools are indispensable components of the whole carbon reservoir, crucial in the organic matter cycle, ecosystem ecology (Sun & Liu, 2020), and the link between carbon as living biomass and soil (Pan et al., 2011). Most biomass estimates resulted from forest inventories, applying existing allometric equations. Allometric equations are developed and applied to forest inventory data to assess forest biomass and carbon stocks, and generalized equations can be found by forest type, biomes, and even species (Vashum et al., 2012).

Forest restoration have been addressed by a few reviews. For example, Wortley, et al (2013) assessed trends in restoration site assessment and identified knowledge gaps in the science. They assessed the extent that key attributes of success, including ecological aspects (e.g. vegetation structure, species diversity and abundance, and ecosystem functioning) and socioeconomic explained restoration success of the projects. From 127 papers assessed (Wortley, et al., 2013), 53 looked at nutrient cycling; 29 included soil structure or stability; 17 addressed dispersal success or mechanisms; six included some measure of pollination; 12 looked at other forms of faunal activity within the site such as reproduction success or feeding; 21 addressed other biological interactions; only nine studies assessed carbon stocks somehow. Aronson et al. (2010) complemented the study by focusing on socioeconomic aspects of ecological restoration, however, it only briefly discussed monitoring. This present study was the first literature review on forest restoration focusing on carbon stock assessment, which is of crucial importance because of the climate change crisis we face nowadays, and because production is correlated to other important aspects of forest restoration, such as biodiversity, ecological functions and ecosystem services (Rosa and Marques, 2022).

Our results map how carbon stock have been addressed to date. Even though carbon stock studies in forest restorations have a global scope, and several types of ecosystems address the topic, the studies are still concentrated in some areas, which may be explained by social and economic aspects, as pointed by Aronson et al. (2010), not by the need to study biomes, which may hinder global policies against climate change and selection of areas and methodologies for restoration projects. With our study, it was possible to find the most used forms in measurements by locations, but also to present which methodologies and places still need to be studied.

Age gradient was well distributed over the studies, but 30-year-old restoration areas were more common. A large number of studies in the same area are necessary to draw comparisons between the methods and to understand trends. A few studies have focused on evaluating the forest ecosystem encompassing all stratums, which may hinder the overall estimates, and be used to standardize regions. As each biome has its own variability, in our work we assessed the methodologies used for carbon stock estimates in the different biomes, so that the main alternatives and methodologies for their region is available for practical endeavors. Besides, monitoring restoration sites over time is of major importance, because carbon stocks dynamics change over time according to environment, restoration method applied. For example, when restoring a pasture to a forest, carbon stock can be negative at the beginning, and after a certain time, the area turns from source to sink (Deng et al. 2016). Therefore, monitoring carbon stock in areas implemented with different methodologies can help us to understand when and how an area turns from carbon source to sink, and what can be done to speed up the process.

As it is known that ecological functions, ecosystem services and biodiversity are correlated to productivity which is correlated to carbon, more studies are needed to locally assess how to improve the carbon sink on each restoration project, so humanity has a better chance to mitigate climate change. The studies on carbon stock dynamics should increase with each passing year, especially with the use of georeferencing methodologies, due to the great relevance of the theme, as well as the search for technological innovations that highlight the importance of forest areas.

2.5. Conclusion

Our results exemplify how carbon stocks have been addressed. Even though carbon stock studies in forest restorations have a global scope, and several types of ecosystems address the topic, they are still concentrated in some areas. An age gradient was well distributed, even though a more significant number of comparisons in the same area and age is fundamental for the real understanding of the estimates found, or even the comparison between different forest restoration methodologies. Concerning the pools, few studies have focused on evaluating the forest ecosystem encompassing all strata, which may hinder the overall values, for example to be used to standardize regions. As each biome has its variability, we make available the methods used for carbon stock estimates for the different biomes, so that future researchers can find the main alternatives and methodologies for their region. The trend is that studies of carbon stock dynamics should increase with each passing year, especially with the use of georeferencing methodologies and the search for technological innovations that highlight the importance of forest areas for the mitigation of global climate change.

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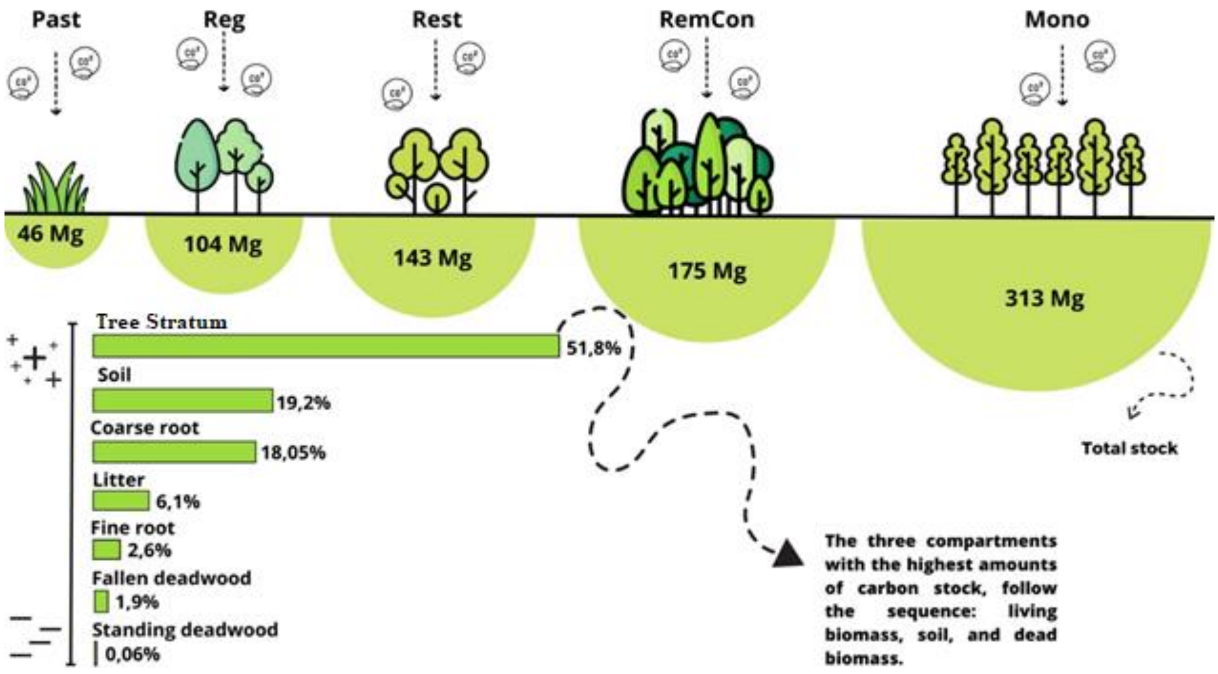
3. CARBON STOCK IN TROPICAL AREAS: POOLS ON DIFFERENT LAND USES

Abstract

Tropical Forest is one of the most diverse biome in the world. Despite their great importance for ecosystem services and climate maintenance, these forest formations are one of the most threatened world. Thus, understanding the quantification of carbon stock in distinct forest formations is relevant to protect the biodiversity and mitigate climate change. Brazilian Atlantic Forest, whose territory is characterized by heterogeneity and diversity of edaphoclimatic conditions and land uses, demand large-scale studies to clarify the contributions of different areas to carbon sequestration, such as pastures, monocultures, remaining fragments, areas of active restoration, and natural regeneration. Hence, this study aimed to quantify the carbon stock in landscapes with different land uses in the Atlantic Forest, comparing the carbon stock between the distinct forest pools. Six study areas throughout São Paulo state, Brazil, were studied, comprising landscapes with different land uses (active restoration, natural regeneration, forest remnant, forest monoculture, and pasture). Carbon stocks were measured in three pools (living biomass, dead biomass matter, and soil organic matter). Total carbon stock was superior in monoculture (313,15 Mg C ha^{-1}), followed, respectively, by forest remnant (175,23 Mg C ha^{-1}), active restoration (143,19 Mg C ha^{-1}), natural regeneration (104,80 Mg C ha^{-1}), and pasture (46,49 Mg C ha^{-1}). Forest areas are important tools for mitigating climate change. In our study, as much as monocultures present the greatest values, forests with higher diversity tend to be more resistant to environmental disturbances, and forest recovery projects should also be encouraged, as in addition to carbon storage, we must also focus on biodiversity conservation, environmental resilience and ecosystem services provided by the natural forest. In addition, protecting existing native forests is critical to maintaining the resilience and health of landscapes.

Keywords. 1. Atlantic Forest 2. Biomass 3. Climate changes 4. Forest restoration 5. Tropical Forest.

Graphical Abstract



The three compartments with the highest amounts of carbon stock, follow the sequence: living biomass, soil, and dead biomass.

Figure 6. Graphical Abstract

3.1. Introduction

Tropical forests are one of the most diverse ecosystems in the world (Rezende et al., 2018; Zwiener et al., 2021), they play an important role in providing indispensable ecosystem services for human well-being (MEA, 2005; Loveridge et al., 2021), such as climate change mitigation (Carlucci et al., 2021), food security (Pires et al., 2021), hydrological regulation (Brauman et al., 2007; Ziegler et al., 2009), remnants connectivity (Arroyo-Rodríguez et al., 2017), and others.

However, these forest formations constitute one of the most threatened ecosystems in the world (Jakovac et al., 2021). In recent decades, various anthropic pressures, especially regarding agricultural and livestock expansion that have been converted, with greater intensity, tropical forests for different purposes, which has reduced, devastated, and fragmented (Tabarelli et al., 2004; Moreno-Mateos et al., 2020; Wagner et al., 2020).

Agriculture requires areas meeting some critera (fertile soils, vegetation, relief, hydrological resources, etc.), which leads to the search for new sites and to the abandonment of those that have already been depleted (Turley et al., 2020; Jakovac et al.., 2021). As a result, we observe the emergence and dissemination of secondary forests (Jakovac et al., 2021), which may be a consequence of natural regeneration, restricted to places of high resilience and, therefore, where natural regeneration is possible due to favorable conditions of soil, climate, water, competitors, etc (Crouzeilles et al., 2017; Chazdon et al., 2020). Also, the secondary forests can be a result of active restoration, through the planting of native species in landscapes with low resilience (Gardon et al., 2020). Both forms of environmental recovery are simple and effective strategies to combat the effects of climate change (Zanini et al., 2021) and to recover biodiversity (Romanelli et al., 2022).

Although many studies have investigated and compared different aspects concerning carbon stock recovery in distinct forest formations, only a few described these patterns covering a significative spatial and temporal scale (Jakovac et al., 2021). Furthermore, studies that quantify the carbon stock in secondary forests considered either only aboveground living biomass (Poorter et al., 2016) or only soil carbon (Don et al., 2011). They rarely include other forest pools (Anderson-Teixeira et al., 2016) as regenerating stratum, herbs, roots, forest litter, and dead matter (Birdsey et al., 2000).

Also, the patterns of biomass storage over time are a non-linear process that can be influenced by the restoration method employed, by numerous biophysical factors, and by the successional stage of the forests (Poorter et al., 2016; Holl & Zahawi, 2014; Gardon et al., 2020). Thus, multiscale studies covering a large gradient of environmental conditions are essential to elucidate patterns of biomass accumulation in the various existing pools (Berenguer et al., 2014; Poorter et al., 2016; Gardon et al., 2020; Zanini et al., 2021).

Hence, most studies have focused on investigating the recovery of biodiversity and the carbon stock of natural forest regeneration, making scientific knowledge less consolidated for forests undergoing through active restoration and neglecting the importance of fragments that persist in deforested landscapes with low resilience (Viani et al. 2015; Gardon et al. 2020). In the Brazilian Atlantic Forest, whose territory is characterized by the heterogeneity and diversity of edaphoclimatic conditions and land uses, large-scale studies are essential to clarify the contributions of different land uses to carbon sequestration, such as pastures, agriculture, monocultures, remaining fragments, areas of active restoration, and natural regeneration.

Therefore, in this study we investigate the potential of different lands use on carbon storage through direct data sampling. The work aimed to quantify the carbon stock in landscapes with different land uses in the Atlantic Forest, comparing the carbon stocks between the distinct carbon pools. Thus, we assessed the potential and contributions of different forest landscapes to carbon storage and the relationship between the forest structure and their total stock.

The hypotheses tested were:

(i) Carbon storage between compartments of all treatments will follow the order: *living biomass > soil > dead biomass*

(ii) The carbon stock will follow the following order in terms of quantity: *Forest Remnant > Forest Monoculture > Active Restoration > Natural Regeneration > Pasture*

3.2. Materials and Methods

3.2.1 Study area

Six study areas throughout São Paulo state, Brazil, were assessed: I. Anhembi; II. Caçapava; III. Campinas; IV. Itatinga; V. Itu; VI. Piracicaba (Figure 7). These areas comprise six landscapes with different land uses. For more information on each study site and its characteristics, consult the supplementary material (Figures S1-S6 and Table S1). All studied areas are in the Atlantic Forest domain (Seasonal Forest). According to the Köppen-Geiger climate classification, they are in type C climates – humid subtropical (Cf, Cw, and Cs) (Alvares et al., 2014). Soil types varied between Red Latosol, Red-Yellow Latosol, and Udult soil (Santos et al., 2011).

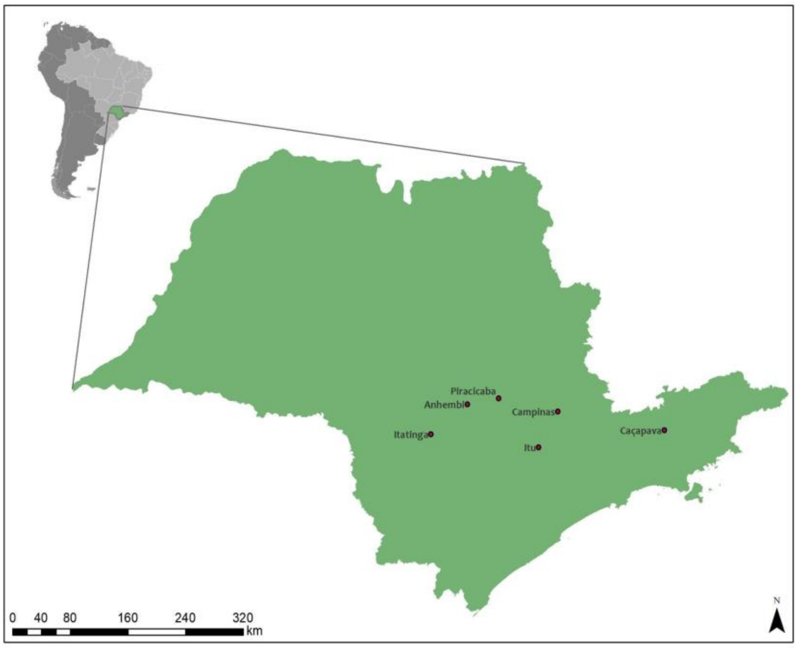


Figure 7. Location of the six studied areas in São Paulo State territoriy, Brazil.

3.2.2 Experimental design

We sampled five different land uses at the study sites: I. Active Restoration (REST): consist of areas planted with native species through active restoration technique, between six and 23 years; II. Natural Regeneration (REG): native forests established spontaneously after area abandonment, with age ranging between seven and 51 years old; III. Forest Remnant (REM): remnant fragments of Seasonal Forests used as reference ecosystems over 35 years old; IV. Forest Monoculture (MONO): forest plantations of exotic species, with ages between eigth and 38 years old; V. Pasture (PAST): managed pasture formed by African grasses used for extensive livestock, with age ranging between eigth and 38 years old. The location of each plot in the six study areas is available in the supplementary material (Appendix I-N).

Technical reports or site interviews confirmed the age of each land use. Plots were georeferenced, so when information about land use and age of the sites was unavailable, Mapbiomass platform was used, which carries land cover data from 1985 to 2020.

3.2.3 Sampling

A total of 117 plots of 30 x 30 m (900 m²) were randomly installed (Figure 8), representing the edaphoclimatic conditions of each land use, along the six study areas. Two to five plots being established in each type of land use, when possible (Table 2, Appendix O).

Table 2. Amount of 30 x 30 m (900 m²) plots installed in São Paulo, Brazil. RES: active restoration; REG: natural regeneration; REM: forest remnant; MON: forest monoculture; PAS: pasture.

Study Area	**Land Use**					**Total**
	REST	**REG**	**REM**	**MONO**	**PAST**	
Anhembi	5	5	2	5	5	**22**
Caçapava	4	4	4	5	4	**21**
Campinas	5	3	3	3	0	**14**
Itatinga	5	5	5	5	0	**20**
Itu	5	3	5	0	5	**18**
Piracicaba	5	2	5	5	5	**22**
Total	**29**	**22**	**24**	**23**	**19**	**117**

Carbon stocks were measured in three forest pools (Figure 9): I. Living Biomass: could be the aboveground biomass comprises all living plant material above the soil (bark, trunks, branches, levaes), and belowgrond biomass encompasses the living roots systems of aboveground biomass; II. Dead Biomass: forest litter, standing and fallen dead wood; III. Soil organic matter: depth ten cm. Measurement methods will be described individually in the next topic.

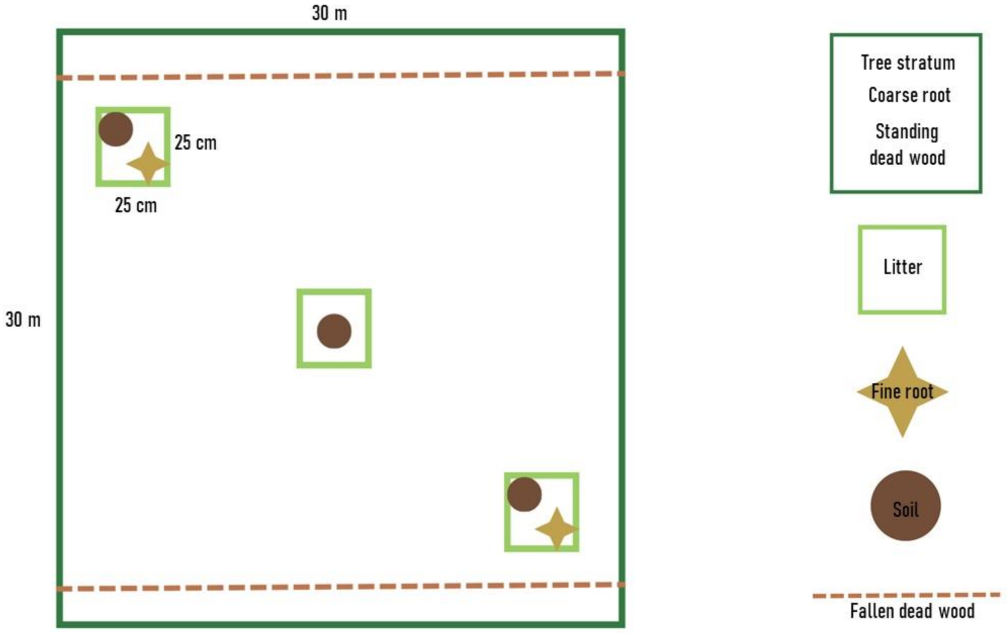


Figure 8. Experimental design to sample the three different pools in the 117 plots installed.

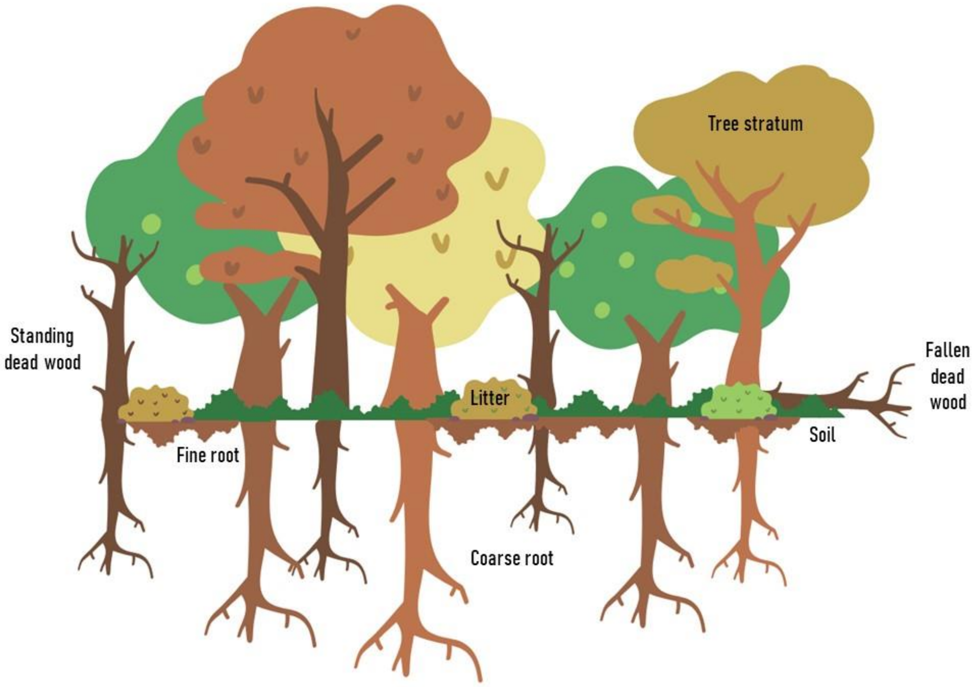


Figure 9. Illustration of the different three forest pools in which the carbon stock was measured

3.2.3.4 Living biomass

3.2.3.4.1 Tree stratum

In the forest inventory plots (Figure 8), individuals of trees at least one stem with a diameter at breast height (DBH)≥5 cm were plated, measured and identified. The DBH and the total height (Ht) were measured, using a diametric tape and a digital hypsometer, respectively. Individuals with more than one stem that met the stipulated inclusion criteria had all stems measured. In addition, botanical materials of each species were collected for later identification in the Herbarium E.S.A. (ESALQ). Taxonomic classification was performed according to the APG IV System (Chave et al. 2006), and spelling of species names was according to "Flora do Brasil" (2022).

To estimate tree biomass, we used three different allometric equations in each landscape, for native species (Chave et al. 2014) (Equation 1), for eucalyptus (Mello et al., 2008) (Equation 2) and for Pinus (Lima et al. 2016) (Equation 3) (Table 3).

Table 3. Allometric equations used to estimate biomass for different landscapes.

Specie	**Equation**
Natives	**Equation 1.** $\mathrm{BAr} = 0{,}0673\ (\mathrm{db}\,.\,\mathrm{DBH}^2.\ \mathrm{Ht})^{0{,}976}$
Eucalyptus	**Equation 2.** $BAr =$ (-4,597) + 1,05811. LN(DBH)^2. Ht
Pinus	**Equation 3.** $BAr =$ -4,02 + 1,83. LN(DBH) + 1,36. LN(Ht). 0,453

Where BAr is tree biomass, db is the basic wood density (g cm^{-3}), DBH is the diameter at breast height (cm), and Ht is the total height (m) of the individual. The db data of each species were obtained using the "getWoodDensity" function of the "BIOMASS" package in R (Réjou-Méchain et al., 2017). When wood density data were unavailable for a given species, we used the mean of the species of the same genus or the same family. For unidentified tree species (about 13% of the total individuals sampled), we used the average wood density for the plot where they were sampled.

Finally, to estimate carbon stock, we converted the biomass values (Mg ha^{-1}) calculated for each individual into carbon stock (Mg C ha^{-1}), considering that the dry tree biomass consists of 47% carbon (IPCC, 2007).

3.2.3.4.2 Coarse root

Coarse root biomass was estimated from the tree stratum biomass using the allometric model developed by Cairns et al. (1997) (Equation 4). Except for the sampled eucalyptus species, in which the coarse root biomass used a parameterized equation for this species by Mello et al. (2008) (Equation 5).

Equation 4. $\mathrm{BRa} = \exp\left(-1{,}085 + 0{,}9256 \ln\left(\mathrm{BAr}\right)\right)$

Equation 5. BRa= -5,21936 + 0,928862. LN(DAP)^2. Ht

Where BRa is coarse root biomass and BAr is tree biomass. Again, to estimate the carbon stock, we converted the biomass values calculated for each individual into a carbon stock, considering that the dry root biomass consists of 47% carbon (IPCC, 2007).

3.2.3.4.3 Fine root

Two points per plot were used to quantify fine roots carbon stock (less than two mm) (Figure 8). At each point, we extracted portions of soil at 0-10 cm layer, totalling 14 cm^3. This is the point-to-point method proposed by Metcalfe et al. (2007), which consists of simultaneously removing all roots with a diameter equal to or less than two mm from the soil in four sessions of two minutes. The fine roots removed were washed, dried, and weighed. We used the Weibull model proposed by Silva et al. (2022) (Equation 6), as it has a good fit to model root extraction in short collection times.

Equation 6. $Rt=a\ (1-\exp(-bt^n))$

The Rt is the cumulative fine root biomass at time t. The a, b, and n are parameters estimated by least squares. For carbon stock estimation, we converted the calculated biomass values into carbon stock, where the fine root dry biomass consists of 47% carbon (IPCC, 2007).

3.2.3.5 Dead biomass

3.2.3.5.1 Forest Littler

The forest litter collection was performed at three points per plot, using wooden frames (25 x 25 cm) (Figure 8). Forest Litter is all the dead material, grass or tree, found on ground surface. The sampled materials were dried in a forced air circulation greenhouse at 40ºC until constant weight. The dry biomass of each sample was quantified in grams using a precision scale. We estimate the biomass values measured into carbon stock considering of 47% carbon (IPCC, 2007).

3.2.3.5.2 Standing dead wood

The standing dead biomass assessement was performed using tree measurement and tree biomass estimates (Figure 8). Therefore, all the dead standing individuals with $DBH \geq 5$ cm had their DBH and HT measured and were classified regarding their Decomposition degree (GD), based on their physical characteristics, according to Harmon & Sexon (1996):

GD1: Decomposition process has not yet started.

GD2: Process of decomposition has begun but keeps the structure.

GD3: Decomposition process is already in the advanced stage.

GD4: Final phase of decomposition, tissue sketch the simple touch.

Volume of the dead tree was estimated using the equation proposed by Chambers et al. (2000) and Palace (2006) (Equation 7):

Equation 7. $V=(\pi\ (0,795^2)\ ((DBH/2)/100)^2\ Ht^{0,818})/\ 0,818$

Where V is volume of the dead tree (m^3), DBH is the diameter at the breast-high (cm), and HT is the total height (m). According to Vieira et al. (2011), the different stages of decomposition reflect different wood densities and carbon stocks (Table 4). To estimate the standing wood biomass, we multiplied the volume of each tree by the basic density of wood regarding its degree of decomposition. For carbon stock, biomass was multiplied by carbon content (Vieira et al., 2011).

Table 4. Density of standing dead wood and fallen dead wood according to the degree of decomposition and each diameter category of thin dead wood. Source: Vieira, et al. (2011).

Decomposition Degree	Standing (g cm^{-3})	Fallen (g cm^{-3})	C contente (%)
1	0,51	0,40	46,95
2	0,42	0,30	46,08
3	0,36	0,22	46,12
4	0,30	0,19	45,05
5	0,28	0,14	45,05
Fallen 5-10 cm	-	0,28	46,05
Fallen 2-5 cm	-	0,21	46,05

3.2.3.5.3 Fallen dead wood

To quantify fallen dead wood, the Van Wagner interception line (1968) method was used, which consists of disposing two known lines (30 m) on the forest floor in the 900 m^2 plots and measuring the diameter of each piece of woody material that crosses the line (Figure 8). Thick fallen dead wood (diameter › 10 cm) were measured all over the line, while thin materials (diameter between two and 10 cm) were recorded in sections encompassing 20% of the line (two sections of three m). Besides, fallen dead wood were classified according to the degree of decomposition (GD) (Keller et al., 2004), where:

GD1: Solid wood with leaves or small branches attached.

GD2: Solid wood with intact bark but without leaves or branches.

GD3: Solid wood, with bark falling.

GD4: Rotten, fragile wood that can break if kicked.

GD5: Rotten and fragile wood, easily broken.

Volume of dead wood was estimated using the formula of the interception line method (Van Wagner, 1968) (Equation 8):

Equation 8. $V=(\pi^2 \sum (dn)^2) / 8 L)$

Where V is volume (m^3 ha^{-1}), dn is diameter of part n at the interception point (cm), and L is the length of the line (m). The interception method formula is based on the probability of dead wood being sampled by the line. This probability is proportional to the length of the line and logs in the plot and is inversely proportional to the size of the sampled area. The method also considers that these logs are cylindrical (Marshall et al., 2000).

To estimate dead wood biomass, we multiply each piece's volume by the basic density of the wood corresponding to its degree of decomposition. Carbon stock was estimated by multiplying biomass by carbon content, as proposed by Vieira et al. (2011). For thin dead wood samples, the degree of decomposition was not considered (Table 3).

3.2.3.6 Soil

To estimate carbon stock in the soil, sample were collected at three points in the plots (Figure 8), at a depth of 0-10cm. A sample per plot was produced by micing the three sample. Then, the soil samples were dried in a forced circulation oven at 40 ºC, macerated, and sieved until reaching a granulometry of 0.250 mm. After, for carbon content analysis, we used the "Leco Truspec Micro" equipment at the Carbon and Nitrogen Laboratory at CENA/USP.

In addition, undisturbed soil samples were collected at the same three points using a volumetric metal ring. Then, the rings were dried at 105°C for 72 hours and weighed on a 0.01 g precision scale. With the determined dry weight value and the known volume of each sample, we obtained the soil density (g/cm^3). Thus, for carbon stock estimation in Mg C ha^{-1} in the soil, we will use the equation proposed by Veldkamp (1994) (Equation 9):

Equation 9. $Cs=(CO\ .\ ds\ .\ es)$

Where Cs is Soil C stock (Mg ha^{-1}), CO is total organic C content at sample depth (%), ds is soil density (g cm^{-3}), and es is the thickness of the considered layer (cm).

3.2.4 Data analysis

Data normality was assessed using the Shapiro-Wilk test. For variance homogeneity, Levene test was used. Considering this, the carbon pools (trees, fine and thick roots, litter, soil, fallen and standing dead wood, total) were compared between the land uses (MONO, REM, REST, REG, and PAST) through non-parametric analysis of variance (Kruskall-Wallis one-way).

When the analysis of variance showed significantly diverged between the typologies ($p < 0.05$), Conover's multiple comparison tests were used ($p \leq 0.05$) to identify these differences. All statistical analyses and calculations were perfomed using R software and the R packages: "PMCMRplus" and "R companion" (Mangiafico & Mangiafico, 2017; Pohlert & Pohlert, 2018; R Development Core Team, 2019). The "Vegan" package was used for floristic richness and diversity (Dixon, 2003).

Spearman correlation test was used to evaluate the type of correlation between the diameter classes (Small: DBH<=15cm; Medium: 15cm>DBH<=30cm; Large: DBH>30cm), diversity, age, and the total carbon stock of each typology. The type of correlation (negative, neutral, and positive) and data dispersion was evaluated using the "chart. Correlation" function of the "Performance Analytics" package in R (R Development Core Team, 2019). Correlations were then categorized according to their level of significance (p-value: 0.001 ***; 0.01 **; and 0.05 *). Before starting the correlation tests, we verified data normality through Shapiro-Wilk using R software (R Development Core Team, 2019).

3.3. Results

3.3.1 Carbon stock

3.3.1.1 Living biomass

For living biomass (Figure 10), the tree stratum differed significantly between the typologies, being the highest in MONO (203.75 Mg C ha^{-1}) and the lowest in PAST (0.27 Mg C ha^{-1}). REM (86.54 Mg C ha^{-1}) was similar to REST (69.54 Mg C ha^{-1}), which was not statistically different from REG (45.13 Mg C ha^{-1}).

Carbon stock in coarse root is directly proportional to the tree stratum. Therefore, the same trend is observed among the typologies, being higher in MONO (65.80 Mg C ha^{-1}), followed by REM (31.43 Mg C ha^{-1}), REST (26.95 Mg C ha^{-1}), REG (17.64 Mg C ha^{-1}) and PAST (0.12 Mg C ha^{-1}). In the fine root, however, REM (6.25 Mg C ha^{-1}) had a higher value, which was significantly similar to PAST (5.36 Mg C ha^{-1}) and REG (4.74 Mg C ha^{-1}). PAST and REG were also statistically equivalent to REST (3.80 Mg C ha^{-1}), while MONO (1.25 Mg C ha^{-1}) had the lowest carbon stock.

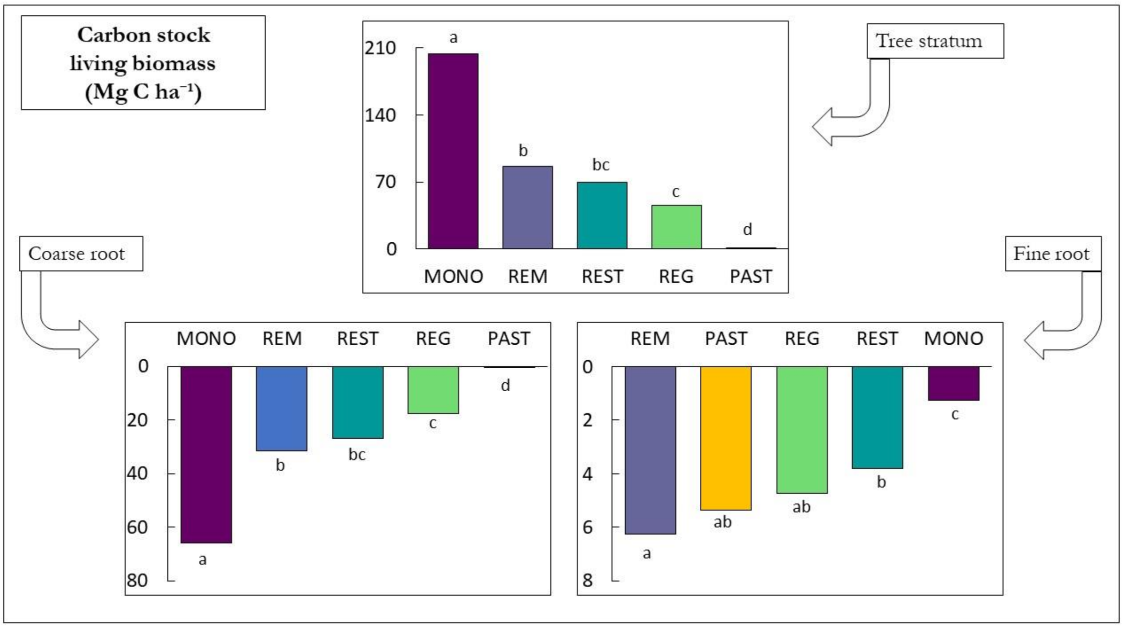


Figure 10. Tree stratum, coarse and fine root average carbon stock in Mg C ha^{-1} for the five different treatments. MONO: Monoculture; REG: Natural Regeneration; REM: Forest Remnant; REST: Forest Restoration; PAST: Pasture. Different letters between study areas indicate a significant difference by the Conover multiple comparison test ($p \leq 0.05$).

3.3.1.2 Dead biomass

For dead biomass (Figure 11), fallen dead wood had the highest quantity of carbon stock in REM, followed by REST, REG, MONO and PAST. For standing dead trees, the highest carbon stock was in REM, REST, REG, PAST and MONO. Forest litter, which represents the most significant stratum within dead biomass, presented the following results: MONO (11.67 Mg C ha^{-1}) and REM (10.54 Mg C ha^{-1}) were statistically equivalent, followed by REST (9.98 Mg C ha^{-1}) and REG (9.24 Mg C ha^{-1}). REST and REG were also similar to the MONO and REM (superior) and to PAST (6.54 Mg C ha^{-1}), which had the lowest results regarding carbon stock.

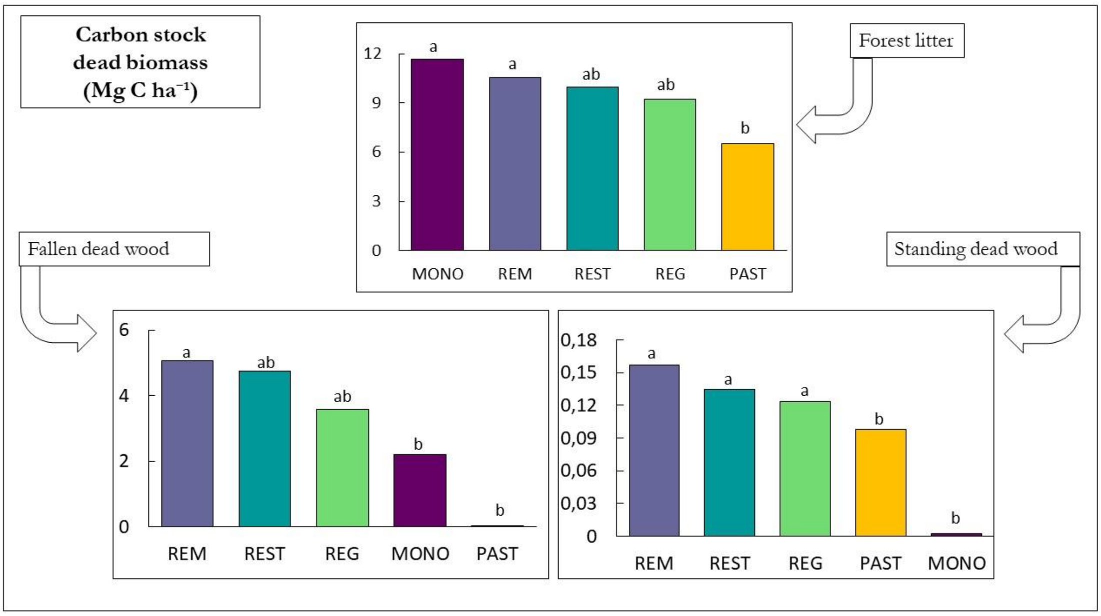


Figure 11. Forest litter, fallen and standing dead wood average carbon stock in Mg C ha^{-1} for the five different treatments. MONO: Monoculture; REG: Natural Regeneration; REM: Forest Remnant; REST: Forest Restoration; PAST: Pasture. Different letters between study areas indicate a significant difference by the Conover multiple comparison test ($p \leq 0.05$).

3.3.1.3 Soil

For soil (Figure 12), REM (35.22 Mg C ha^{-1}) had the highest carbon stock even though it had the lowest soil density (1.12 g/cm^3), followed by PAST (34.18 Mg C ha^{-1}), MONO (28.43 Mg C ha^{-1}), REST (28.02 Mg C ha^{-1}) and REG (24.31 Mg C ha^{-1}). REM, it was statistically different from REG. REST, MONO, and PAST were not statistically different and to REG and REM.

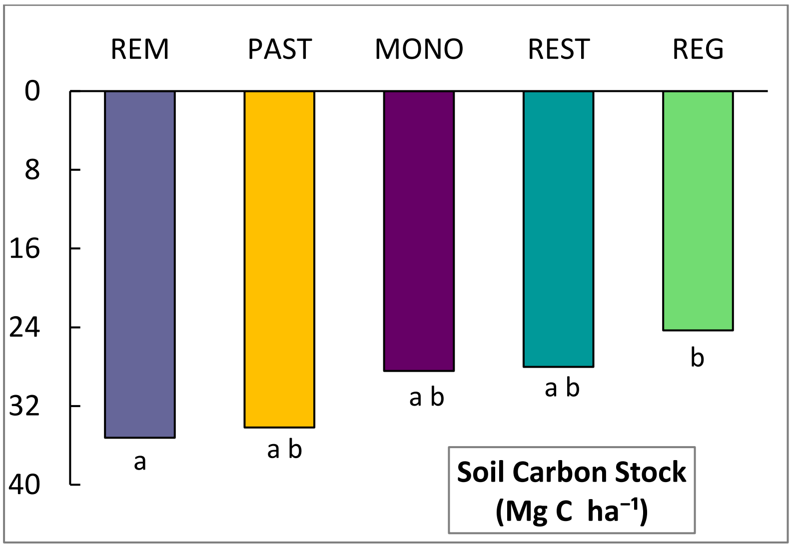


Figure 12. Soil average carbon stock (Mg C ha^{-1}) at 10cm depth on the five different treatments. MONO: Monoculture; REG: Natural Regeneration; REM: Forest Remnant; REST: Forest Restoration; PAST: Pasture. Different letters between study areas indicate a significant difference by the Conover multiple comparison test ($p \leq 0.05$).

3.3.1.4 Total carbon stock

Total Carbon stock was superior in MONO (213,15 Mg C ha^{-1}), followed, by REM (175,23 Mg C ha^{-1}), REST (143,19 Mg C ha^{-1}), REG (104,80 Mg C ha^{-1}), and PAST (46,49 Mg C ha^{-1}) (Figure 13).

Results were calculated from the biomass of the forest pools and their respective carbon and soil stock values. Living biomass was the most representative stratum in MONO (86% of the stock), REM (71%), REST (70%), and REG (65%). Followed by soil, which representes 23% of the carbon stock in REG, 20% in REM, 19% in REST, and 9% in MONO, and dead biomass, which represents 12% in REG, 11% in REST, 9% in REM, and 5% in MONO. For PAST, soil (74%) was the pool with the highest storage, followed by dead biomass (14%) and live tree biomass (12%). MONO carbon stock was significantly superior to others. REM and REST showed similar values but differed from REG and PAST.

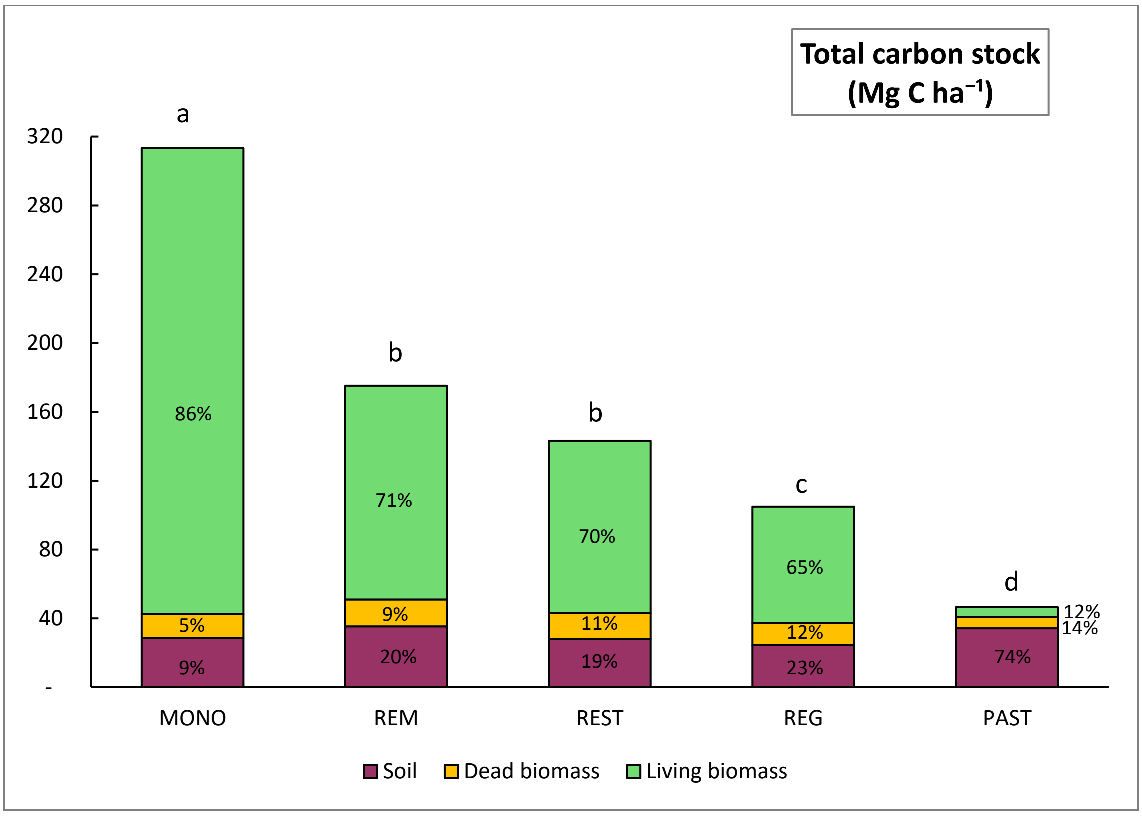


Figure 13. Average total Carbon stock (Mg C ha^{-1}) in the pools in the different treatments. MONO: Monoculture; REG: Natural Regeneration; REM: Forest Remnant; REST: Forest Restoration; PAST: Pasture. Different letters between study areas indicate a significant difference by the Conover multiple comparison test ($p \leq 0.05$).

3.3.2 Abundance of diameter classes

In general, small (DBH<=15cm) individuals (9599) contributed the most to total abundance in all typologies, followed by medium (15cm>DBH<=30cm) classes (2990) and finally, by the large (DBH>30cm) ones (351 individuals) (Figure 14). REST had the highest number of small-sized individuals (3442), not different statisticaly from REG (2613), which was also not significantly different from REM (2117). REM also had similar results to MONO (1352), which differed from PAST (75). MONO (964) was the treatment with highest value and was significantly similar to REST (956). REST was equivalent to REM (617), which differed from REG (450) and

PAST (three). Regarding large individuals, MONO (117) was also superior, followed by REM (107) and REST (95), which were significantly similar to each other and statistically different from REG (32) and PAST (0).

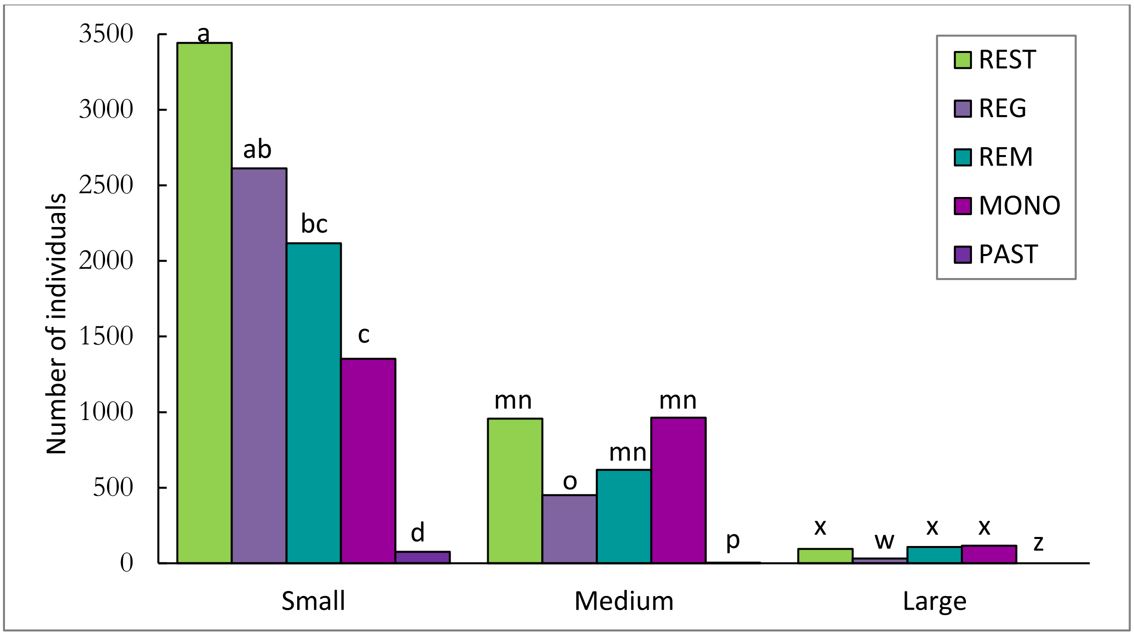


Figure 14. Number of individuals per diameter class according to the treatment. Small (DBH<=15cm); Medium (15cm>DBH<=30cm); Large (DBH>30cm). MONO: Monoculture; REG: Natural Regeneration; REM: Forest Remnant; REST: Forest Restoration; PAST: Pasture. Different letters between study areas indicate a significant difference by the Conover multiple comparison test ($p \leq 0.05$).

Regarding each diameter class contribution in carbon stock, although the abundance of individuals was inferior in the large class, carbon allocated by them had a positive correlation in REM, MONO, REG, and REST (Table 5), indicating that the large individuals account for a large portion of the carbon stock in the areas. For medium ones, there was a positive correlation in REM, MONO, REG, and REST. The individuals with the smallest diameter class had a negative correlation with carbon stock in MONO and PAST. We can observe that, although REST and REG have the highest abundance of total individuals, as they have a smaller diameter, the carbon stock is smaller.

Table 5. Pearson correlation (R²) between the total carbon stock and class size in the different diameters of each typology, being small (DBH<=15 cm), medium (15cm>DBH<=30cm), and large (DBH>30cm).

Typology	Diameter class	R^2	*p*-value
REM	Small	0,26	-
	Medium	0,43	0,01
	Large	0,90	0,001
MONO	Small	-0,47	0,05
	Medium	0,60	0,01
	Large	0,60	0,001
REG	Small	0,19	-
	Medium	0,82	0,001
	Large	0,65	0,001
REST	Small	0,025	-
	Medium	0,80	0,001
	Large	0,77	0,001
PAST	Small	-0,44	0,05
	Medium	-0,44	-
	Large	-0,44	-

3.4. Discussion

The forest recovery has been gaining global importance as one of the main strategies for mitigating climate change. Thus, understanding the potential for carbon stock over a gradient of landscapes, indicating how effectively carbon is stocked from the atmosphere, is necessary to develop reforestation policies and practices.

Our study in the Atlantic Forest compared land uses in different landscapes. The result for the total carbon stock of the areas indicates that sites in forest monoculture (213.15 Mg C ha^{-1}) stored more carbon than the forest remnants (175.23 Mg C ha^{-1}). On the other hand, regarding the recovery methodologies, active restoration (143.19 Mg C ha^{-1}) was similar to the remnant and superior to natural regeneration (104.80 Mg C ha^{-1}), being the tree stratum the most representative in both areas. Pasture areas (46.49 Mg C ha^{-1}), had the lowest storage, with soil being the main source of carbon stock.

Brown et al. (2020) indicated that forest plantations under low-intensity management reach higher carbon stock levels, presenting a better potential for mitigating climate change when compared to secondary forests undergoing natural regeneration. Positive correlations were also found between carbon stock and larger diameters, indicating that larger individuals are mainly responsible for carbon storage. Acoording to Arcanjo et al. (2022), the presence of species with a larger size may indicate long-term increase in biomass accumulation at restoration sites.

Thus, although active restoration has more individuals (4993) than other land uses, and natural regeneration has the second one (3095), there is a predominance of small individuals, representing 76% and 84% of the total, respectively. Thus, the predominance of smaller individuals can justify the lower amount of carbon stock on these typologies regarding the tree stratum when compared to the remnants and monocultures since there is a relationship between DBH and the height of the species, resulting, consequently, in higher carbon stock in taller individuals, even if they are less abundant (Arcanjo et al., 2022; Brown et al., 2020).

Areas urdergoing through the active restoration, although younger, had similar storage to the remaining fragments, indicating that restored forests play a relevant role in carbon sequestration and, consequently, in mitigating climate change (Brancalion et al. 2016; Matos et al. 2020). Deng et al. (2016) also concluded, in this sense, that the dynamics of carbon sequestration by different land uses were not affected by the age of their individuals. Therefore, different species, management, and monitoring in the areas are factors that help with greater intensity in the storage effectiveness (Gardon et al., 2020).

Active restoration presented a higher total carbon stock than natural regeneration. However, there were no discrepancies in the biomass stock for any pools (tree stratum, root, dead wood, root, forest litter, and soil), indicating that both restoration strategies are equally effective and complementary. It is estimated that if we protect these forests for the next 40 years, the total carbon accumulated would be enough to offset emissions from fossil fuels and industrial processes throughout Latin America from 1993 to 2014 (Chazdon et al., 2016).

Currently, policies to combat climate change have been increasingly being embraced and designed for environmental agendas on a national and international scale (Chazdon et al., 2016). Hence, ecological restoration by natural regeneration or active methods has gained more attention as an indispensable tool to fulfill such commitments through the sequestration and storage of atmospheric carbon in its biomass (Alexander et al., 2011), as well as in areas of monoculture (Bukoski et al., 2022).

However, the high investment cost and low cost-effectiveness of restoring ecosystems through active restoration techniques may not pay off in cases where restoration aims for carbon storage and climate change mitigation (Chazdon et al. 2016; Brancalion et al. 2021). Likewise, despite the low cost of implementation, the carbon stock of the forest undergoing natural regeneration can vary greatly depending on several biotic factors and environmental conditions that make its success uncertain (Arroyo-Rodrígues et al., 2017).

Nevertheless, even though the remaining forest fragments are excellent carbon sinks, storing high amounts in their biomass, they continue to be neglected in environmental policies, with liana management, enrichment and densification into fragments (Cesar et al, 2017). Therefore, the investment in the restoration of existing fragments is fundamental and urgent, as they accumulate more biomass than it would be possible to obtain in the short term and at a low cost in active and passive restoration plantations.

Although monoculture areas showed the best carbon storage, probably because of the production cycles, soil improvements and rapid growth, they are just one alternative, among many others forestation (Sacco et al., 2020). However, from the perspective of economic benefits to landowners, such as the sale of wood, this can be an attractive strategy for mitigating climate change, acting as an encouragement to restore forest cover (Vicente et al., 2021). Furthermore, payment for environmental services arising from the maintenance of natural vegetation cover can also constitute an incentive proposal for producers, providing benefits that cover the three pillars of sustainability (economic, social, and environmental).

Nonetheless, emissions from harvesting activities, the decomposition of residues in the areas, and short-lived wood products can reduce or nullify these benefits (Sonne, 2006). Also, exotic species usage in monoculture systems presents a relevant biodiversity loss compared to other recovery forms (Kanowski et al., 2005). Chazdon and Guariguata (2016) corroborate that one of the challenges to the implementation of reforestation processes is the use of exotic tree species, and, on a large scale, the adoption of tree planting in monoculture systems can present conflicts with the precepts of forestry restoration in the social and ecological scope.

Forests with higher diversity tend to be more resistant and resilient to environmental disturbances, and it must be considered when assessing the durability of the carbon stock (Osuri et al., 2020). Therefore, studies that evaluate how diversity can improve long-term climate and biodiversity conservation results should be a priority (Bukoski et al., 2022). Additionally, if we focus the choice of recovery method only on the amount of carbon stored, we can suggest that monoculture, active restorations, or regenerations are equivalent in mitigating climate change (Bonner et al., 2013; Hulvey et al., 2013; Zanini et al., 2021). Yet, other factors must be considered when choosing the methodology, such as cost (Brancalion et al., 2021), quality in terms of capture reliability in the face of disturbances (Osuri et al., 2020), and biodiversity conservation (Narain and Maron, 2018).

Thus, again, we emphasize the need to protect the remaining fragments as the most viable strategy for carbon stock. If there is a need to recover new areas, the restoration of natural forests, whether by active or passive methods, is the most indicated because these forest formations also help to conserve biodiversity and generate other ecosystem services.

3.5. Conclusion

Different land uses in the Atlantic Forest were evaluated in this study, with forest monoculture areas being those that stored the most carbon, followed by forest remnants. Among the recovery methodologies, the active restoration presented similar values to the remnants and superior to the natural regeneration. Pasture areas, on the other hand, had the lowest storage, however efficient the soil stock. We conclude that forest areas are important tools for mitigating climate change. As much as monocultures present the greatest values, forest recovery projects should also be encouraged, as in addition to carbon storage, we must also focus on biodiversity conservation, environmental resilience and ecosystem services provided by the natural forest. In addition, protecting existing native forests is critical to maintaining the resilience and health of landscapes.

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4. ENVIRONMENTAL AND FINANCIAL GAIN RURAL LANDOWNERS CAN OBTAIN WITH THE ENVIRONMENTAL RECOVERY OF THEIR PERMANENT PRESERVATION AREAS

Abstract

Carbon markets are a matter to motivate greenhouse gas emissions offsets by financially compensating those who adopt sustainable practices that reduce or remove GHG emissions. Brazil does not yet have policies setting the regulatory Market, which often leads to doubts about how to participate. With this, the objective of this study was to estimate the potential carbon sequestration and the financial gain that can be obtained from carbon credits generated trought forest restoration of Permament Preservation Areas (PAA). Mapping Bananal/SP city allowed found out that PPA are occupied mainly by pastures (51.41%), followed by forest formations (48.16%), and finally by a small portion of silviculture (0.31%). If all these areas are restored and conserved, the carbon storage of the city is approximately 3 million tonC worthing to 150 million total dollars, with forest hectare value estimated from 510 to 8,500 US$/ha, depending on the market. The values presented are crucial to encourage the participation of rural producers in carbon markets, even though the current methodology deals with APP and RL areas not with additionality and normally prevents participation in the carbon market, our study presents the potential of these areas in providing the service and believes that financial incentives are one of the main attractive ways to recover these areas. Thus, we concluded that participation in reforestation programs and in the carbon market should be encouraged and allowed, as the recovery of these areas would generate other environmental services for the property in terms of climate, soil, water and biodiversity.

Keywords. 1. Forest Restoration 2. Ecosystem Services 3. Carbon Stock 4. Payment Environmental Services 5. Carbon Market

4.1. Introduction

Global climate dynamics have been changing due to the increase in the planet's average temperature, leading to an increase in extreme climate events and rising sea levels. The cause of this warming is the high emission of greenhouse gases (GHG), primarily caused by the burning of fossil fuels, land use changes, and agriculture (IPCC, 2022). It is estimated that anthropogenic activities have caused an estimated global warming of 1.0°C above normal levels, with a potential increase of 1.5°C between 2030 and 2052 if no modifications are made on anthropic activities (IPCC, 2018). In order to reverse these scenarios, various international agreements and programs have been established to mitigate climate change by reducing emissions and concentrations of gases in the atmosphere (UNFCCC, 2015).

One way to enhance the effectiveness of achieving these goals is through climate investments (Hong et al., 2020), being carbon markets one of the main global strategies (Calel, 2013). However, in Brazil, although Bill 528/2021, which defines the Brazilian Carbon Emission Reduction Market (MBRE), is currently under consideration in the Congress, there is still no existing legislation regulating it in the country, and participation is currently only possible in voluntary markets (Simoni, 2009). In these markets, organizations voluntarily to offset their emissions through various projects promoting renewable energy systems, forest restoration, and conservation (Paiva et al., 2015). There is a trend of exponential growth in these initiatives (Peters-Stanley & Yin, 2013), as international awareness of climate change and its impacts on the economy and financial markets has increased in recent years, shaping investment decisions and market participation (De Souza Cunha et al., 2021).

Because of the importance of forests in carbon sequestration (Gardon et al., 2020), forest restoration projects play a prominent role in global commitments (CBD, 2011; UN, 2012; UNCCD, 2013), as trees remove high levels of atmospheric CO2 and store it as carbon in their biomass (Crowther et al., 2015). For example, the Bonn Challenge is a global goal to restore 350 million hectares of degraded and deforested landscapes by 2030 (IUCN, 2015; Chazdon et al., 2017). Brazil has set a target of restoring 12 million hectares of degraded areas by 2030 (UN, 2015), and current legislation requires rural landowners to restore areas of permanent preservation (PPA) and legal reserves (RL). Nevertheless, it is estimated that 20 million hectares of legally protected areas need to be restored (Soares-Filho et al., 2014). Thus, a form of incentives for forest restoration and environmental conservation through payment programs for environmental services (PES) are extremely necessary to improve the environmental conditions of the planet.

Therefore, the objective of this study was to estimate the potential carbon sequestration and the financial gain that can be obtained from carbon credits generated trought forest restoration of Permament Preservation Areas (APP) in the municipality of Bananal, São Paulo, Brazil. The results have the potential to contribute to the identification of effective strategies for forest restoration and to stimulate the adoption of these measures by rural landowners, benefiting both the environment and the local economy.

4.2. Materials and Methods

4.2.1 Study area

The study was conducted in the municipality of Bananal (22°40'51" S, 44°19'25" W), located in the Paraíba Valley in the far east of São Paulo State. The climate in the region is classified as mesothermal (Köppen, 1948), with an average annual precipitation between 1,500 and 2,000 mm, mild summers, and no dry season (Cfb). The average annual temperature varies from 20 to 23 °C, with absolute minimums ranging from 0 °C to 4 °C, which allows frost. The region is part of the Atlantic Forest domain and is predominantly composed of Dense Montane and Upper Montane Rainforest. However, since the 18th century, the municipality has suffered from deforestation and human occupation, initiated by the sesmaria system and coffee cultivation. However, unsustainable practices have led to soil impoverishment and agricultural unsuitability. Since 1870, the region has been primarily dedicated to livestock farming (César et al., 2012), which is the current main land use.

4.2.2 Land use and land cover in the APP

To assess land use and land cover in PPA área encompassing the municipality of Bananal/SP, the mapping of water-related APPs provided by the Fundação Brasileira para o Desenvolvimento Sustentável (FBDS) was utilized. This mapping was developed based on supervised classification of RapidEye satellite images from 2013, with a viewing scale of 1:10,000. The classification was conducted following the requirements of the Brazilian Law for Protection of Native Vegetation (Law 12.651/2012), considering the minimum width values established by the legislation. The environmental liabilities in the municipality can be represented by the sum of areas that make up the APPs in Bananal. These areas include Built-up Areas, defined as urban areas (Figure 15), which will not be considered in our study as their territorial conditions cannot be altered. By law any land use change before 2008 do note need to be restores back to native fragmente, even if met the criteria for PPA. Additionally, there are Anthropized Areas, which are areas devoid of native vegetation cover (Figure 16), Silvicuture forestry areas (Figure 17), and Forestry formations of native species (Figure 18).

Figure 15. Built-up areas in PPAs in the municipality of Bananal/SP.

Figure 16. Anthropized areas existing in PPAs in the municipality of Bananal/SP.

Figure 17. Silvicuture forestry existing in PPAs in the municipality of Bananal/SP.

Figure 18. Forestry formations of native species of PPAs in the municipality of Bananal/SP

4.2.3 Storage estimates and economic value

Current carbon stock in PPA of the municipality of Bananal was made using the area data obtained from the municipal land use and land cover survey, multiplied by the estimated carbon stock values indicated by the second chapter of this theses for different land uses, 175 Mg C ha^{-1} for forest formations, 45 Mg C ha^{-1} for anthropized areas and 303 Mg C ha^{-1} for silviculture. From this step, we estimated how much the municipal carbon stock would increase if the entire PPA were restored.

For the financial estimates, we calculated the annual opportunity cost of the land. For the anthropized area, it was estimated based on land rental prices for livestock farming in the Bananal region, using official data from the Institute of Agricultural Economics of São Paulo (São Paulo, 2017), which was US$73,6/ha/year. As for the forest formations and silviculture areas, based on field knowledge, we assumed that there is currently no opportunity cost for these areas. We also calculated the restoration costs for these areas based on values obtained by Molin et al. (2018) for pasture areas, where the cost of natural regeneration is US$1.250/ha, and the cost of active restoration is US$3.750/ha for the Atlantic Forest. Considering the difference in the forest area to be restored, we estimated the monetary value of the carbon that could be traded by rural landowners through the restoration of their areas. Carbon price in the voluntary Market varies from US$3 to US$5/T CO_2, and according to future projections, it is expected to range from US$20 to US$50 (Busch et al., 2019). We performed calculations ranging from US$3 to US$50 per ton of CO_2.

4.3. Results

The main land use and land cover in the APP of the municipality of Bananal is anthropized land (51.41%) with 9,032.71 hectares, which refers to areas devoid of native vegetation. In the region, these areas are primarily used as pastures, often degraded. The second most common land use is forest formations (48.16%) with 8,462.87 hectares, mainly found in the part of the municipal territory located in the Serra da Bocaina and within the Conservation Units of the municipality. Silviculture follows in third place (0.31%) with 53.52 hectares. It was initiated in the 1990s as an attempt to establish monocultures of pine and eucalyptus in the region but it was unsuccessful due to difficulties in access and market demand. Currently, these areas are abandoned. Lastly, the urban built-up area (0.12%) covers 22.36 hectares, which we excluded from our analysis (Figure 19).

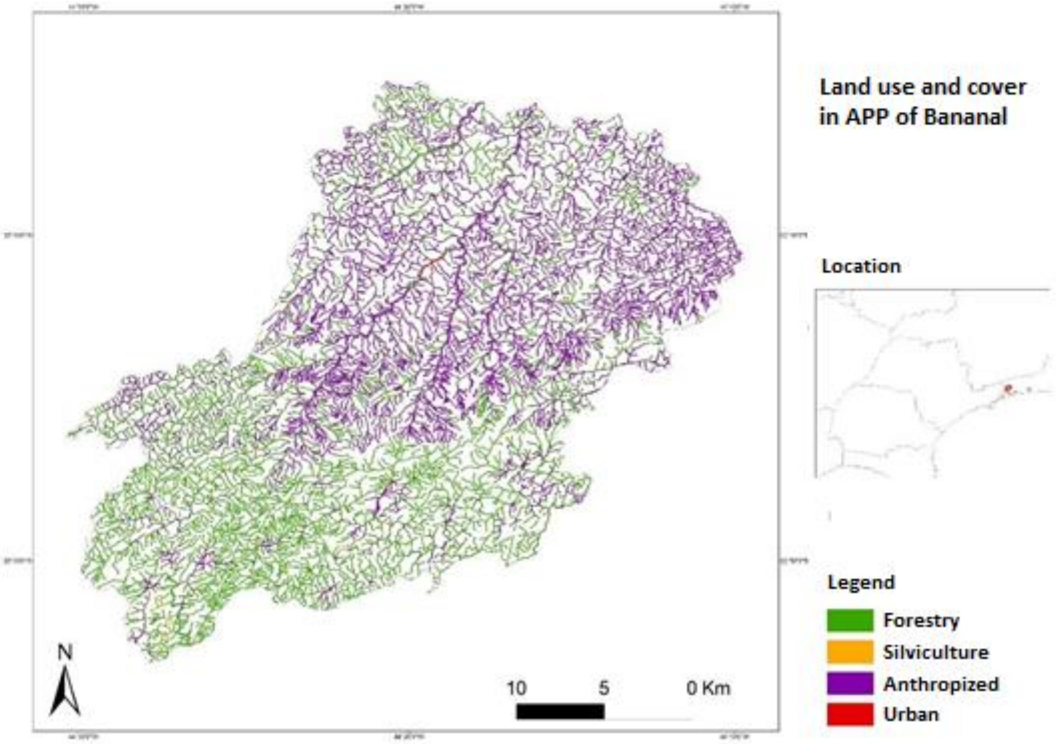

Figure 19. Mapping of land use and land cover in APPs in the municipality of Bananal, SP, according to Fundação Brasileira para o Desenvolvimento Sustentável data.

Currently, the municipality can generate approximately $664,807.46 per year from pasture areas, and potentially earn between $4 million and $71 million through possible PES programs. Based on territorial calculations, the current carbon stock of the municipality is estimated as approximately 1.9 million tons of carbon (tonC), which would increase to approximately 3 million tons of stored carbon if all PPA areas were restored. For restoration, natural regeneration without human intervention, apart from isolating the area from degrading factors such as livestock and fire, is recommended. The estimated cost for fencing this area is $12 million. By restoring the areas, the municipality can generate ecosystem service revenue from carbon and PES ranging from nine million dolares to $150 million (Table 6). Regarding the potential earnings per hectare of restored and/or conserved forest, the estimated values range from $510 to $8,500 per hectare, depending on the market participation.

Table 6. Estimates of Carbon Stock and Economic Value of the different classes of land use in the municipality of Bananal/SP.

Land use and cover	**Forestry Formation**	**Silviculture**	**Anthropized**
Area (ha)	8.462,87	53,52	9.032,71
Present carbon stock (MgC/ha)	1.481.002,25	16.216,56	406.471,95
Estimate of Carbon stock with restored (MgC/ha)	1.438.687,90	9.366,00	1.580.724,25
Minimum amount that can be received with PSA (US$/tonC)	4.316.063,70	28.098,00	4.742.172,75
Maximum amount that can be received with PSA (US$/tonC)	71.934.395,00	468.300,00	79.036.212,50

4.4. Discussion

We acknowledge that there are several variables that could be estimated to make our model more realistic, such as field measurements of biomass and carbon stock values, in adition to the fact that not all of the municipality's PPA can be restored. However, we believe in the potential of our work to present financial opportunities to rural landowners that can be obtained through the restoration of legally preserved areas. With the increase in global warming, strategies to reduce the effect of high greenhouse gas (GHG) concentrations in the atmosphere (UNFCCC, 2015) need to be set. The first agreement reached was the Kyoto Protocol in 1997, which established guidelines for the carbon market aiming to motivate international commitment to reduce GHG emissions. It set maximum emission quotas for countries and allowed carbon credit trading and quota purchases. However, only developed countries participated (UNFCCC, 2007). In 2015, a new international treaty, the Paris Agreement, was created, recognizing that climate change posed an urgent and potentially irreversible threat. It involved 195 nations and aimed for greater cooperation in achieving more effective and appropriate goals (UNFCCC, 2015).

Since 2016, Brazil has committed to reducing GHG emissions up to 43% by 2030, compared to 2005 levels, achieving 45% renewable energy usage and restoring 12 million hectares of forests (UN, 2015). However, according to the data presented at COP27, the country did not meet the targets, and projections are pessimistic, as emissions have increased instead of decreasing since then (IPCC, 2022). Nevertheless, despite the Brazilian government going against global trends, there is a growing awareness of global climate change that shapes investments and markets (De Souza Cunha et al., 2021), and prospects for the carbon market are extremely favorable (Anis et al., 2022).

However, unlike many regions where carbon is treated as a commodity, Brazil has not yet established an "emissions trading system" market (World Bank, 2016). At the national level, the Law No. 12.187/2009, established the National Policy on Climate Change (PNMC) and foresees the Development of the Brazilian Emission Reduction Market (MBRE) (BRAZIL, 2009a), currently under consideration in the National Congress. In addition, the General Coordination of Environment and Climate Change of the Economic Policy Secretariat of the Ministry of Finance (COMAC/SPE/MF) is implementing the proposal of the PMR-Brazil Project (Partnership for Market Readiness) to promote innovation, actions, and funds for climate change mitigation and adaptation (Melo & Silva, 2018). The implementation of Clean Development Mechanism (CDM) projects, which will help in pricing and valuing the market within the country (Anis et al., 2022), is also underway. According to the World Bank's 2020 report, carbon ton was traded on average $10, and it is estimated that with regularization and global awareness, this value will reach $50 by 2030 (Busch et al., 2019). However, without current legislation, carbon is traded in voluntary markets (Simoni, 2009), where organizations have their emissions offset initiatives through different projects for renewable energy systems, forest restoration, and conservation projects (Paiva et al., 2015), allowing carbon credits trading through certified financial contracts (Anis et al., 2022).

The choice of the strategy adopted is crucial in determining the cost-benefit of restoration, which, although significantly overlapping with the potential price of traded carbon, can be at least partially offset if carbon stocks are traded. Restoration is an expensive process, but many of the conclusions drawn in this study are based on incomplete accounting of its benefits. In many cases, the cost-benefit analysis of restoration activities is based solely on financial values, rather than the broader set of values that reflect many of the non-commercial benefits that restoration provides (De Groot et al., 2013).

In addition to the benefits that can be translated into financial values, with ecological and sociocultural benefits. The ecological benefits are related to the restoration of ecosystem health, while the sociocultural benefits arise from human perception and attitude towards the importance of ecosystem services (De Groot et al., 2010; Nieto-Romero et al., 2014). Thus, this practice promotes environmental improvement, which is reflected directly in agricultural productivity. It restores the physical and chemical conditions of the soil, improving water infiltration, which results in improved water quality and quantity. It also contributes to carbon storage and climate change mitigation. With forest restoration and increased biodiversity, there is greater availability of food, thus increasing the diversity and richness of fauna and promoting greater seed dispersal. Sociocultural benefits include job creation along the restoration chain, economic diversification, improved quality of life, positive impacts on human health, scenic beauty of the landscape, and possibilities for connection with nature, among others.

However, most of these benefits are only realized in the long term, which influences landowners' decision-making to restore their areas, even when it is required by law. In this context, PES programs emerge as a tool to promote the conservation of natural resources (Wunder, 2005), rewarding those who produce or maintain environmental services and providing monetary incentives to those who would not usually provide such services (Pagiola et al., 2002). According to Wunder et al. (2008), the most common PES programs in the world focus on carbon storage, biodiversity protection, protection of watersheds, and scenic beauty. Regardless of focus, most of these programs use ecological restoration to achieve their conservation goals, promoting this practice worldwide. By offering payments for their services, landowners are encouraged to invest in restoring and caring for natural ecosystems, creating an economic stimulus for restoration.

PES programs operate at different sociopolitical scales that involve various social actors (Reed et al., 2009; Reyers et al., 2010), and they are embedded in a broad context that requires the incorporation of these actors' perceptions in the decision-making process, especially regarding the valuation of environmental services (Menzel and Teng, 2010; Young et al., 2013). The effectiveness of PES is linked to the incorporation of interests, knowledge, and limitations of the actors involved in the program planning stage, as they can help to shape its structure, identify possible conflicts, and define the dynamics of benefit and cost distribution (Corbera et al., 2008). However, including these factors in the early stages rarely occurs, and as a consequence, there may be a lack of understanding among the actors regarding the program's impacts, risking their trust in it and affecting the project's viability, its impacts, and legitimacy. Furthermore, including the actors in the planning process is important to reduce errors and biases in monitoring, quantification, and impacts of interventions, as well as to ensure the long-term sustainability of the program (Pullin and Knight, 2005; Fisher et al., 2011; Quétier and Lavorel, 2011; Fisher and Brown, 2015). The knowledge of local actors who depend on environmental resources is essential to identify solutions that can be accepted within their social context, which will be more appropriate compared to top-down public policies (Thompson et al., 2016; De Vente et al., 2016).

For the proper functioning of a PES program, it is crucial to consider the social and cultural context of the implementation site (Salk et al., 2016), including the participation of local actors in decision-making processes. Furthermore, the social context can determine the most suitable type of incentive to be used, whether it's direct cash payments, technical assistance, crop insurance, access to credit, contribution to community services, or even a combination of these (Engel et al., 2008; Wong, 2014; Chantarat, 2011; To et al., 2012; Yang et al., 2015). It is worth noting that providing of incentives can affect users' intrinsic motivation, which would impact long-term resource conservation if the incentives were no longer provided (Frey and Jegen, 2001; Muradian et al., 2013). There are two possibilities for this scenario: the first is resource degradation (Salk et al., 2016), and the second is a change in awareness, attitudes, or livelihoods (Rode et al., 2015).

"But can small producers make money with forest restoration and conservation of their PPA?" This is the main question that arises when the subject is the carbon market, and the answer is not so positive. As currently in Brazil, the ongoing market is voluntary, one of the most common is the VERRA methodology, the owners can participate but the area to be restored needs to be additional, that is, in a baseline scenario this area would be forested, and it is not the case of the areas required by law. In addition, they need to be able to develop, design and implement a forest restoration or conservation project, which allows them to issue certified carbon credits in the market (Verra, 2023). As a result, receiving carbon credits just by restoring PAA is difficult. One way to make projects viable and reduce costs for small-scale producers is through participation in grouped projects (Verra, 2023) and restoration incentive programs, as the costs of restoring these ecosystems can be very high, and often the carbon market prices do not cover the costs of restoration (Brancalion et al., 2021). With this approach, producers can restore degraded areas on their property, in addition to those required by law, more cheaply and sustainably, certify their credits, and efficiently trade them. However, there is a debate about this, since even though the PPA and RL areas are required by law to be conserved, the study show that more than 20 million hectares of these areas are degraded (Soares-Filho et al., 2014), and participation in incentive programs only as a form of additionality makes the restoration and preservation of these areas even more unfeasible.

In our case study, the municipality of Bananal is part of the Paraíba do Sul River Basin and is located between the two largest industrial and population centers in the country, with the highest number of inhabitants and the highest national GDP (Brancalion et al., 2012), which are the capitals of Rio de Janeiro and São Paulo. This region has been extensively degraded in past centuries, first through large-scale coffee production when it was one of the country's main producers, and later due to charcoal exploitation (São Paulo, 1998), which led to significant deforestation of the Serra da Bocaina. Most of its territory is covered by degraded and unproductive pastures (César et al., 2012). Additionally, it is whitin the Brazilian Atlantic Forest, the most deforested biome in the country (Ribeiro et al., 2009). However, despite this historical degradation process, the municipality still has areas of preserved forests, as it is home to the Bananal Ecological Station, part of the mountainous region of the Serra da Bocaina National Park, and several Private Natural Heritage Reserves. All these Conservation Units contribute to forest conservation in the region.

Due to its national economic and environmental importance, the region benefits from and participates in various programs that assist in regional development and environmental restoration projects. The main project in the region is the Pact for the Restoration of the Atlantic Forest, a national movement that aims to restore 15 million hectares of Atlantic Forest by 2050 through partnerships with governments, companies, and local communities (Rodrigues et al., 2009). There is also the Atlantic Forest Connection Project, which currently carries out actions in the municipality and aims to increase the protection of biodiversity and water resources, combat climate change, promote native vegetation conservation, adoption of more productive systems, and improvement of conservation unit management (INEA, 2011). Additionally, there are opportunities to be part of various programs and investment projects for the recovery, preservation, and conservation of water resources in the Paraíba do Sul basin. As a result of its land use history, the Bananal region is favored because it still contains large forested areas that facilitate natural regeneration. Therefore, passive restoration methods, such as simply fencing the area to be restored, are recommended, which will facilitate and greatly reduce implementation costs (Brancalion et al., 2012; Brancalion et al., 2021).

In addition, from the study estimates, we show the capacity of the municipality to contribute to climate change, and the financial valuation of the recovery of PAA can be a great incentive for the environmental contribution. With that, we encourage the flexibility of the rules for APP and RL, considering a minimum value for the commercialization of these credits. More than ever, the carbon market and PES programs are expanding, becoming key tools for forest conservation and the restoration of new areas. Rural landowners who recognize the opportunity to participate in these programs can add value to areas that must be preserved and contribute to mitigating climate change while improving the environmental conditions of their property, such as increasing biodiversity, conserving soil, and improving water quality. Therefore, to ensure long-term resource conservation, it is important for incentives to be accompanied by awareness and environmental education programs. It is also essential to involve local actors and incorporate their needs and perceptions into the planning of PES programs.

4.5. Conclusion

The search for strategies that help mitigate climate change are essential for the conservation of human life on Earth, with the stimulus being forest restoration in degraded areas one of the most efficient ways. The present case study carried out in the municipality of Bananal, presented estimates of the possible forest recovery of pastures areas at different levels of degradation in PPA, which could store approximately 3 million tons of carbon, and the traded value of carbon could vary from almost 9 to 150 million dollars, and the value of the forest hectare estimated at 510 to US $8,500/ha, depending on the market in which it participates. The values presented are crucial to encourage the participation of rural producers in carbon markets, even though the current methodology deals with APP and RL areas not with additionality. Our study presents the potential of these areas and believes that the financial incentive is the main attraction for the recovery of these areas, generating, in addition to economic gain, also environmental gain both on the property and in global terms.

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5. FINAL CONSIDERATION

Carbon storage is currently one of the main processes for mitigating climate change, with tropical forests primarily responsible for providing this ecosystem service. Due to this global importance, much is seen about the subject, whether in congresses, research topics, or even in the commercial world, companies bring this subject and use it as a marketing strategy. In our research, we approach the topic on several fronts, either through a bibliographic review and access to data on how the topic is being treated worldwide, or through a case study and the real contribution of different land uses and compartments in carbon storage, or even the estimation of a potential economic gain, in addition to the environmental one, with the participation of small producers in the carbon market.

In chapter 1, a bibliometric review was developed with the objective of providing an overview of the carbon stock monitoring process in forest restoration projects stratified in the main areas of interest. The review was based on a database of 107 articles, encompassing 26 countries and 7 biomes, which were published from 2003 to 2022. The age of the restoration projects ranged from 6 months to over 100 years, with the active method of restoration the most applied. As for the assessment of the strata, only 31 studies evaluated all the different forest compartments for carbon stock, which could lead to a possible overestimation or underestimation of the actual storage data by areas. By examining the methodology by biome, we were able to identify patterns around the most common ways to restore areas based on region, which can help researchers and decision makers to identify the methods most likely to succeed in each biome. We note that there is a difference in the number of studies per region, and many areas around the world lack carbon stock monitoring.

Chapter 2, we take into account the importance of the Atlantic Forest for biodiversity conservation and climate change mitigation, we investigate the contributions of different land uses, such as pastures, monocultures, remaining fragments, areas of active restoration and natural regeneration, to the stock of carbon, evaluating values between the different compartments, as living biomass, dead biomass and soil. Study sites in the state of São Paulo were assessed, with the total carbon stock found in the following order: monoculture (213.15 Mg C ha^{-1}), forest remnant (175.23 Mg C ha^{-1}), active restoration (143.19 Mg C ha^{-1}), regeneration (104.80 Mg C ha^{-1}) and pasture (46.49 Mg C ha^{-1}). Although monoculture areas show the highest carbon storage, forests with greater diversity tend to be more resistant to environmental disturbances and should be considered when assessing the durability of the carbon stock. In addition, we must also consider the conservation of biodiversity, the resilience of the environment and the ecosystem services offered. Thus, alternatives such as natural regeneration (active or passive) and the protection of remaining fragments should be privileged.

In Chapter 3, we estimate the environmental and financial gain that can be obtained by paying for the environmental service of carbon storage through forest restoration of Permanent Preservation Areas (PPA) for rural landowners, since the carbon market is in increasing expansion, being one of the main keys to preserve forests and the restoration of new areas, adding value to areas that must be preserved, helping to mitigate climate change, as well as to improve the environment of your property. In our estimates we find that for the municipality of Bananal, landowners can earn from 510 to 8,500 US$ per hectare of forest, depending on the market in which they participate and we encourage the flexibility of the commercialization of credits generated by PPA in the carbon market, since it would be a greater attraction for the preservation of these areas.

Based on our results, we recommend that future studies should: i. Consider new areas of the globe in stocking estimates; ii. To assess the carbon stock within the different compartments; iii. Present the importance of biodiversity conservation in view of the restoration of new areas; iv. Case study on the implementation of producer participation in the carbon market. In addition, the important message that our work brings is that forests are really one of the main sources of carbon stock, forest restoration being potentially significant, as it stimulates the implementation of new areas, in addition to being part of the obligations legal by environmental legislation, generates great environmental benefit and can also bring financial gain.

APPENDICES

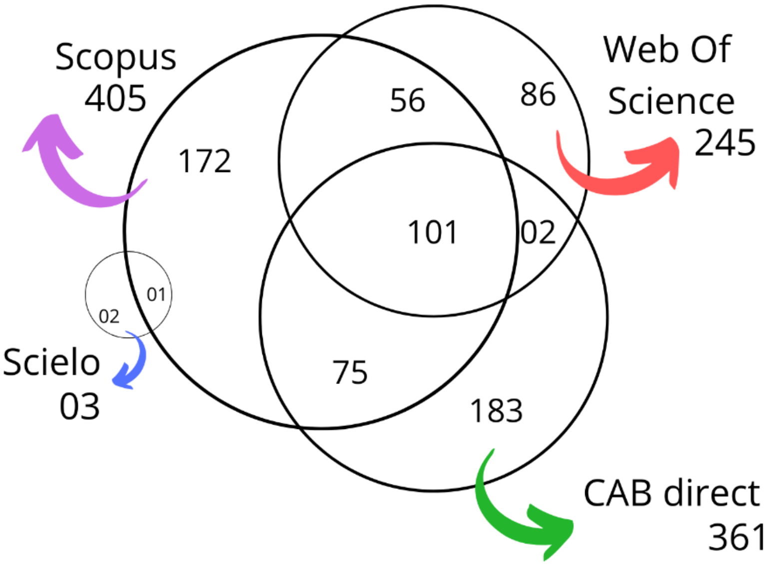
Appendix A. Interpretation of Kappa analysis, according to Landis and Koch (1977).

Kappa	Interpretation
< 0	No agreement
0.0 – 0.20	Slight agreement
0.21 – 0.40	Fair agreement
0.41 – 0.60	Moderate agreement
0.61 – 0.80	Substantial agreement
0.81 – 1.00	Near perfect agreement

Appendix B. Search strategies to retrieve papers on the data sources (Web of Science, Scopus, CAB Direct, and SciELO). All searches were limited to papers published in English, Spanish, and Portuguese, conducted on September 18, 2021.

Bibliometric Source	Search query
Web of Science (Core collection: SCI-E, SSCI, ESCI); Every year; Articles and reviews)	*TOPIC ((“restoration ecology*” OR “ecological restoration*” OR “forest restoration*”) AND (“carbon stock*” OR “carbon storage*”))* **245 records**
Scopus (Every year; Articles and reviews)	*TITLE-ABS-KEY ((“restoration ecology*” OR “ecological restoration*” OR “forest restoration*”) AND (“carbon stock*” OR “carbon storage*”))* **405 records**
SciELO Citation Index (Every year; Articles and reviews)	*TOPIC “restoration ecology*” OR “ecological restoration*” OR “forest restoration*” OR “restauração ecológica*” OR “ecologia da restauração*” OR “restauração florestal*” AND “carbon stock*” OR “carbon storage*” OR “estoque de carbono*”* **3 records**
CAB Direct (Every year; Articles and reviews)	*All FIELDS (“restoration ecology*” OR “ecological restoration*” OR “forest restoration*”) AND (“carbon stock*” OR “carbon storage*”)* **361 records**
	Total Records: 1014

Appendix C. Total number and overlap of references retrieved from the four bibliographic data sources (Web of Science, Scopus, CAB Direct, and SciELO).



Appendix D. Examples of some references excluded from this study after analyzing their titles, abstracts, and keywords, and the reason why they were excluded.

Reference	Reason for exclusion
Abdallah M.A.B., Mata-González R., Noller J.S., Ochoa C.G. (2020). Ecosystem carbon in relation to woody plant encroachment and control: Juniper systems in Oregon, USA. Agriculture, Ecosystems and Environment. 290.	Carbon stocks in grassland restorations.
Gardon, F.R.; Santos, R.F.; Rodrigues, R.R. (2020). Brazil's forest restoration, biomass and carbon stocks: a critical review of the knowledge gaps. Forest Ecology and Management, 426.	Systematic review.
Mackey, B., Kormos, C.F., Keith, H., et al. (2020). Understanding the importance of primary tropical forest protection as a mitigation strategy. Mitigation and Adaptation Strategies for Global Change.	Importance of protecting primary tropical forests for climate change.
Paolucci L.N., Pereira R.L., Rattis L., Silvério D.V., Marques N.C.S., Macedo M.N., Brando P.M. (2019). Lowland tapirs facilitate seed dispersal in degraded Amazonian forests. Biotropica, 51:245-252.	Facilitating natural regeneration in degraded tropical forests.
Li Q., Chen D., Zhao L., Yang X., Xu S., Zhao X. (2016). More than a century of Grain for Green Program is expected to restore soil carbon stock on alpine grassland revealed by field 13C pulse labelling. Science of the Total Environment, 550:17-26.	Carbon partitioning rates and turnover in soils.
Docherty K.M., Gutknecht J.L.M. (2019). Soil microbial restoration strategies for promoting climate-ready prairie ecosystems. Ecological Applications, 29(3).	Recovery of soil microbiology in grasslands.
Galatowitsch S.M. (2009). Carbon offsets as ecological restorations. Restoration Ecology, 17(5):563-570.	Issue of opinion on carbon market in ecological restorations.
Hansen V.D., Nestlerode J.A. (2014). Carbon sequestration in wetland soils of the northern Gulf of Mexico coastal region. Wetlands Ecology and Management. 22: 289-303.	Soil carbon sequestration in wetland restorations.
Staples, Timothy L.; Mayfield, Margaret M.; England, Jacqueline R.; et al. (2020). Comparing the recovery of richness, structure, and biomass in naturally regrowing and planted reforestation. Restoration Ecology, 28(2):347-357.	Biomass stock in natural regeneration.

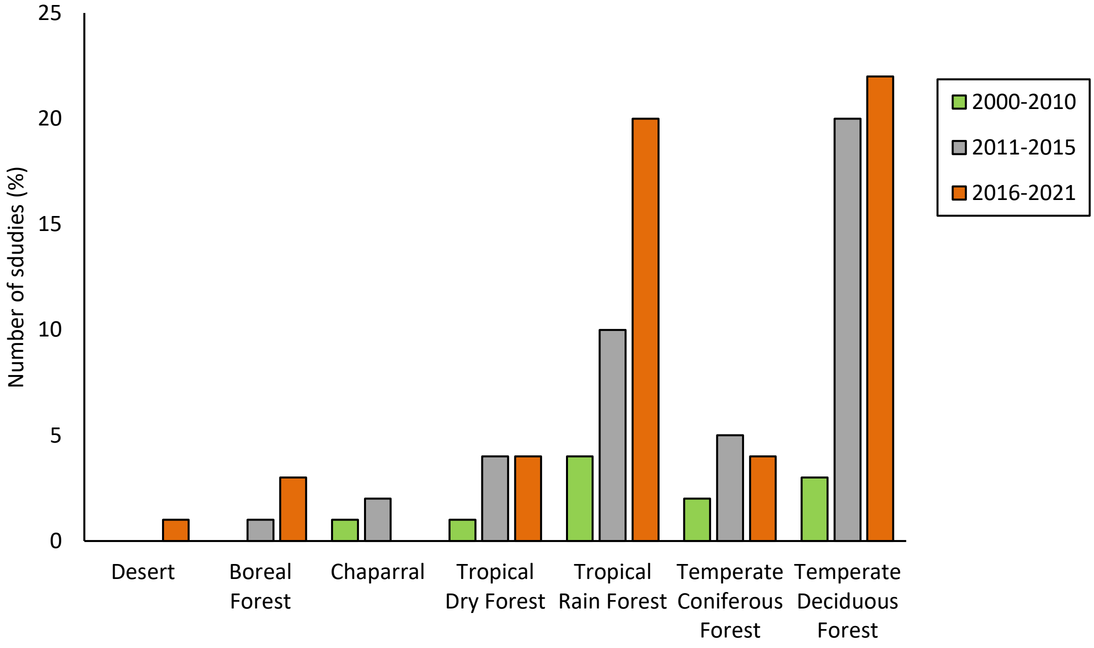
Appendix E. Number of papers assessed in this study by Journal.

Journal	Number of Studies	Journal	Number of Studies
Forest Ecology and Management	14	Carbon Balance and Management	1
Restoration Ecology	7	Chinese Journal of Applied Ecology	1
Ecological Engineering	6	Environmental Management	1
Catena	4	Environmental Research Letters	1
Ecological Applications	4	Eurasian Journal of Soil Science	1
Agriculture, Ecosystems and Environment	3	Forest Ecosystems	1
Ecosphere	3	Forest Science And Technology	1
Ecological Management and Restoration	3	Forestry	1
Geoderma	3	Global Change Biology	1
Journal of Environmental Management	3	Investigacion Agraria Sistemas y Recursos Forestales	1
Journal of Mountain Science	3	Journal of Arid Land	1
Shengtai Xuebao / Acta Ecologia Sinica	3	Journal of Cleaner Production	1
Canadian Journal of Forest Research	2	Journal of Food, Agriculture and Environment	1
Eurasian Soil Science	2	Journal of Forest and Environmental Science	1
Floresta	2	Journal of Forest Research	1
Forest	2	Journal of Vietnamese Environment	1
Journal of Forestry Research	2	Land Degradation & Development	1
Journal of Soils And Sediments	2	Land Use Policy	1
Plos ONE	2	Minerals	1
Science of The Total Environment	2	New Zealand Journal of Ecology	1
Acta Agriculturae Scandinavica	1	Pacific Science	1
Agroforestería en las Américas	1	Plant and Soil	1
American-Eurasian Journal of Agricultural & Environmental Sciences	1	Polish Journal of Ecology	1
Applied Soil Ecology	1	Remote Sensing	1
Australian Journal of Basic and Applied Sciences	1	Revista de Biologia Tropical	1
Biodiversity and Conservation	1	Soil Biology and Biochemistry	1
Biology Bulletin	1	Urban Forestry and Urban Greening	1
Canadian Journal of Applied Ecology	1	-	-

Appendix F. Number of papers assessed in this study by country.

Country	**Number of studies**	**Country**	**Number of studies**
China	43	Canada	1
United States	15	Colombia	1
Brazil	9	Korea	1
India	6	Scotland	1
Russia	4	Hawaii	1
South Africa	3	Indonesia	1
Australia	3	Iceland	1
Ethiopia	3	Italy	1
Costa Rica	2	Mexico	1
Japan	2	Micronesia	1
New Zealand	2	Panama	1
Argentina	1	Tanzania	1
Camaroon	1	Vietnam	1

Appendix G. Number of studies released by year interval (2000-2010; 2011-2015; 2016-2021) by domains.



Appendix H. List of papers assessed in this study in descending order according to the year of publication, authors, title, and journal name.

Publication number	Authors	Title	Journal	Year of publication
1	Downey, A.E.; Groffman, P.M.; Mejía, G.A.; Cook, E.M.; Sritrairat, S.; Karty, R.; Palmer, M.I.; McPhearson, T.	Soil carbon sequestration in urban afforestation sites in New York City	Urban Forestry and Urban Greening	2021
2	Rao, K.S.; Semwal, R.L.; Ghoshal, S.; Maikhuri, R.K.; Nautiyal, S.; Saxena, K.G.	Participatory active restoration of communal forests in temperate Himalaya, India	Restoration Ecology	2021
3	Song, X.; Shi, S.; Lu, S.; Ren, R.; He, C.; Meng, P.; Zhang, J.; Yin, C.; Zhang, X.	Changes in soil chemical properties following afforestation of cropland with Robinia pseudoacacia in the southeastern Loess Plateau of China	Forest Ecology and Management	2021
4	Victor, A.D.; Valery, N.N.; Francois, A.I.; Vanissa, T.D.C.; Paulidore, M.; Louis, Z.	Dynamics of soil organic carbon stock under different types of Savannah agrosystems in the Sudano-Sahelian zone of Cameroon	Eurasian Journal of Soil Science	2021
5	Ward, E.B.; Doroski, D.A.; Felson, A.J.; Hallett, R.A.; Oldfield, E.E.; Kuebbing, S.E.; Bradford, M.A.	Positive long-term impacts of restoration on soils in an experimental urban forest	Ecological Applications	2021
6	Warner, E.; Lewis, O.T.; Brown, N.; Green, R.; McDonnell, A.; Gilbert, D.; Hector, A.	Does restoring native forest restore ecosystem functioning? Evidence from a large-scale reforestation project in the Scottish Highlands	Restoration Ecology	2021
7	Zanini, A.M.; Mayrinck, R.C.; Vieira, S.A.; de Camargo, P.B.; Rodrigues, R.R.	The effect of ecological restoration methods on carbon stocks in the Brazilian Atlantic Forest	Forest Ecology and Management	2021
8	Zhang, S.; Deng, Q.; Wang, Y.-P.; Chen, J.; Yu, M.; Fang, X.; He, H.; Chen, J.; Xu, P.; Wang, S.; Yan, J.	Linkage of microbial living communities and residues to soil organic carbon accumulation along a forest restoration gradient in southern China	Forest Ecosystems	2021
9	Abegaz, A.; Tamene, L.; Abera, W.; Yaekob, T.; Hailu, H.; Nyawira, S.S.; Da Silva, M.; Sommer, R.	Soil organic carbon dynamics along chrono-sequence land-use systems in the highlands of Ethiopia.	Agriculture Ecosystems & Environment	2020
10	Ahirwal, J.; Kumar, A.; Maiti, S.K.	Effect of fast-growing trees on soil properties and carbon storage in an afforested coal mine land (India).	Minerals	2020
11	Foster, D.E.; Battles, J.J.; Collins, B.M.; York, R.A.; Stephens, S.L.	Potential wildfire and carbon stability in frequent-fire forests in the Sierra Nevada: trade-offs from a long-term study	Ecosphere	2020
12	Lan, Z.; Zhao, Y.; Zhang, J.; Jiao, R.; Khan, M.N.; Sial, T.A.; Si, B.	Long-term vegetation restoration increases deep soil carbon storage in the Northern Loess Plateau	Shengtai Xuebao/ Acta Ecologica Sinica	2020
13	Preston, M.D.; Brummell, M.E.; Smenderovac, E.; Rantala-Sykes, B.; Rummey, R.H.M.; Sherman, G.; Basiliko, N.; Beckett, P.; Hebert, M.	Tree restoration and ecosystem carbon storage in an acid and metal impacted landscape: chronosequence and resampling approaches.	Forest Ecology and Management	2020
14	Ryzhova, I.M.; Telesnina, V.M.; Sitnikova, A.A.	Dynamics of Soil Properties and Carbon Stocks Structure in Postagrogenic Ecosystems of Southern Taiga during Natural Reforestation	Eurasian Soil Science	2020
15	Safar, N.V.H.; Magnago, L.F.S.; Schaefer, C.E.G.R.	Resilience of lowland Atlantic forests in a highly fragmented landscape: Insights on the temporal scale of landscape restoration.	Forest Ecology and Management	2020

16	Xiao, S.; Zhang, J.; Duan, J.; Liu, H.; Wang, C.; Tang, C.	Soil organic carbon sequestration and active carbon component changes following different vegetation restoration ages on severely eroded red soils in subtropical China	Forests	2020
17	Yan, M.; Fan, L.; Wang, L.	Restoration of soil carbon with different tree species in a post-mining land in eastern Loess Plateau, China	Ecological Engineering	2020
18	Cha, S.; Kim, C.B.; Kim, J.; (...); Koo, N.; Kim, Y.S.	Land-use changes and practical application of the land degradation neutrality (LDN) indicators: a case study in the subalpine forest ecosystems, Republic of Korea	Forest Science and Technology	2020
19	Hu, N.; Lan, J.	Impact of vegetation restoration on soil organic carbon stocks and aggregates in a karst rocky desertification area in Southwest China	Journal of Soils and Sediments	2020
20	Huang, Y.; Xin, Z.	Effects of different ecological restoration patterns on soil organic carbon in gullies of Loess Plateau	Shengtai Xuebao/ Acta Ecologica Sinica	2020
21	Matos, F.A.R.; Magnago, L.F.S.; Aquila Chan Miranda, C.; (...); Meira-Neto, J.A.A.; Edwards, D.P.	Secondary forest fragments offer important carbon and biodiversity cobenefits	Global Change Biology	2020
22	Sanquetta, C.; Bastos, A.; Sanquetta, M.; Dalla Corte, A.P.; Queiroz, A.	Carbon stock and removal of co2 in young stands of forest restoration in Rondônia	Floresta	2020
23	Wang, S.J.; Chen, M.K.; Cao, R.; Cao, Q.B.; Zuo, Q.Q.; Wang, P.; Yang, B.; Zhao, S.	Contribution of plant litter and soil variables to organic carbon pools following tropical forest development after slash-and-burn agriculture	Land Degradation and Development	2020
24	Zenebu, H.; Fassil, K.; Ibrahim, F.; Zenebe, A.; Girmay, G.; Emiru, B.	Acacia dominated area exclosures enhance the carbon sequestration potential of degraded dryland forest ecosystems	Journal of Forest and Environmental Science	2020
25	Zhang, X.; Adamowski, J.F.; Liu, C.	Which slope aspect and gradient provides the best afforestation-driven soil carbon sequestration on the China's Loess Plateau?	Ecological Engineering	2020
26	Jones, I.L.; DeWalt, S.J.; Lopez, O.R.; Bunnefeld, L.; Pattison, Z.; Dent, D.H.	Above- and belowground carbon stocks are decoupled in secondary tropical forests and are positively related to forest age and soil nutrients respectively	Science of the Total Environment	2019
27	Lyu, M.; Xie, J.; Giardina, C.P.; Vadeboncoeur, M.A.; Feng, X.; Wang, M.; Ukonmaanaho, L.; Lin, T.-C.; Kuzyakov, Y.; Yang, Y.	Understory ferns alter soil carbon chemistry and increase carbon storage during reforestation with native pine on previously degraded sites	Soil Biology and Biochemistry	2019
28	McCauley, L.A.; Robles, M.D.; Woolley, T.; Marshall, R.M.; Kretchun, A.; Gori, D.F.	Large-scale forest restoration stabilizes carbon under climate change in Southwest United States	Ecological Applications	2019
29	Osipov, A.F.; Tuzhilkina, V.V.; Dymov, A.A.; Bobkova, K.S.	Phytomass and Organic Carbon Stocks in the Middle Taiga Spruce Forests during Restoration after Clear Cutting	Biology Bulletin	2019
30	Osuri, A.M.; Kasinathan, S.; Siddhartha, M.K.; Mudappa, D.; Raman, T.R.S.	Effects of restoration on tree communities and carbon storage in rainforest fragments of the Western Ghats, India	Ecosphere	2019

31	Pang, D.; Cui, M.; Liu, Y.; Wang, G.; Cao, J.; Wang, X.; Dan, X.; Zhou, J.	Responses of soil labile organic carbon fractions and stocks to different vegetation restoration strategies in degraded karst ecosystems of southwest China	Ecological Engineering	2019
32	Swinfield, T.; Lindsell, J.A.; Williams, J.V.; Harrison, R.D.; Agustiono, H.; Gemita, E.; Schönlieb, C.B.; Coomes, D.A.	Accurate measurement of tropical forest canopy heights and aboveground carbon using Structure from Motion	Remote Sensing	2019
33	Telesnina, V.M.; Zhukov, M.A.	The influence of agricultural land use on the dynamics of biological cycling and soil properties in the course of postagrogenic succession (Kostroma Oblast)	Eurasian Soil Science	2019
34	Wang, Y.; Mao, N.; Wang, J.; Huang, L.; Jia, X.; Shao, M.	Spatial variability of soil carbon and water storage across loess deposit catenas in China's Loess Plateau region.	Canadian Journal of Soil Scienc	2019
35	Yang, Y.; Dou, Y.; Cheng, H.; Na, S.	Plant functional diversity drives carbon storage following vegetation restoration in Loess Plateau, China	Journal of Environmental Management	2019
36	Zhang, H.; Deng, Q.; Hui, D.; Wu, J.; Xiong, X.; Zhao, J.; Zhao, M.; Chu, G.; Zhou, G.; Zhang, D.	Recovery in soil carbon stock but reduction in carbon stabilization after 56-year forest restoration in degraded tropical lands	Forest Ecology and Management	2019
37	Cao, J.J.; Zhang, X.F.; Deo, R.; Gong, Y.F.; Feng, Q.	Influence of stand type and stand age on soil carbon storage in China's arid and semi-arid regions	Land Use Policy	2018
38	de Azevedo, A.D.; Francelino, M.R.; Camara, R.; Pereira, M.G.; Leles, P.S.S.	Carbon stock in forest restoration areas of the Atlantic Forest	Floresta	2018
39	Han, X.; Gao, G.; Chang, R.; Li, Z.; Ma, Y.; Wang, S.; Wang, C.; Lü, Y.; Fu, B.	Changes in soil organic and inorganic carbon stocks in deep profiles following cropland abandonment along a precipitation gradient across the Loess Plateau of China	Agriculture, Ecosystems and Environment	2018
40	Jitendra Ahirwal; Maiti; S. K.	Development of Technosol properties and recovery of carbon stock after 16 years of revegetation on coal mine degraded lands, India	Catena	2018
41	Liu, X.P.; Zhang ,W.J.; Cao, J.S.; Yang, B.; Cai, Y.J.	Carbon sequestration of plantation in Beijing-Tianjin sand source areas	Journal of Mountain Science	2018
42	Liu, Y.L.; Zhu, G.Y.; Deng, L.; Chen, L.; Shangguan, Z.P.	Effects of natural vegetation restoration and afforestation on soil carbon and nitrogen storage in the Loess Plateau, China	Chinese Journal of Applied Ecology	2018
43	Mehta, H.; Kumar, R.; Dar, M.A.; Juyal, G.P.; Patra, S.; Dobhal, S.; Rathore, A.C.; Kaushal, R.; Mishra, P.K.	Effect of geojute technique on density, diversity and carbon stock of plant species in landslide site of North West Himalaya	Journal of Mountain Science	2018
44	Mokria, M.; Mekuria, W.; Gebrekirstos, A.; Aynekulu, E.; Belay, B.; Gashaw, T.; Bruning, A.	Mixed-species allometric equations and estimation of aboveground biomass and carbon stocks in restoring degraded landscape in northern Ethiopia	Environmental Research Letters	2018
45	Rayome, D.D.; Ostertag, R.; Cordell, S.	Enhancing Aboveground Carbon Storage and Invasion Resistance through Restoration: Early Results from a Functional Trait-Based Experiment	Pacific Science	2018

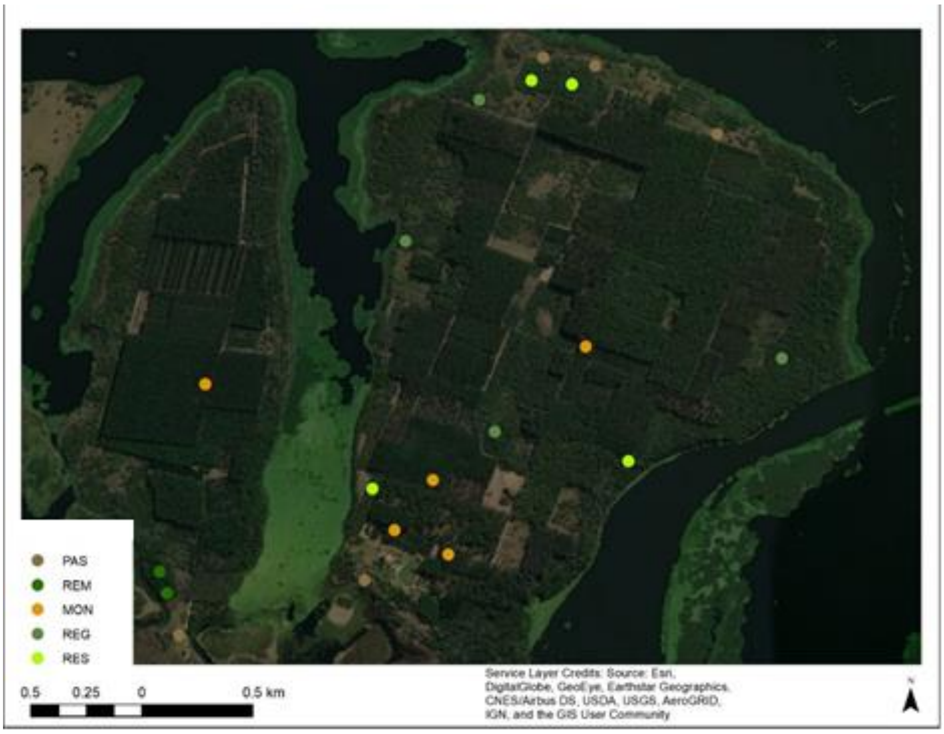
46	Yang, Y.; Dou, Y.; Na, S.	Testing association between soil bacterial diversity and soil carbon storage on the Loess Plateau	Science of the Total Environment	2018
47	Brunori, A. M. E.; Sdringola, P.; Dini, F.; Ilarioni, L.; Nasini, L.; Regni, L.; Proietti, P.; Proietti, S.; Vitone, A.; Pelleri, F.	Carbon balance and Life Cycle Assessment in an oak plantation for mined area reclamation	Journal of Cleaner Production	2017
48	Cao, Y.; Chen, Y.	Ecosystem C:N:P stoichiometry and carbon storage in plantations and a secondary forest on the Loess Plateau, China	Ecological Engineering	2017
49	Nie, X.; Li, Z.; Huang, J.; Huang, B.; Xiao, H.; Zeng, G.	Soil organic carbon fractions and stocks respond to restoration measures in degraded lands by water erosion	Environmental Management	2017
50	Pang, X.; Huang, J.; Zhao, Q.; Feng, D.F.; Bao, W.; Tian, G.	Ecosystem carbon stock across a chronosequence of spruce plantations established on cutovers of a high-elevation region	Journal of Soils and Sediments	2017
51	Liu, S.; Dong, Y.; Cheng, F.; Yin, Y.; Zhang, Y.	Variation of soil organic carbon and land use in a dry valley in Sichuan province, Southwestern China	Ecological Engineering	2016
52	Matzek, V.; Warre,n S.; Fisher, C.	Incomplete recovery of ecosystem processes after two decades of riparian forest restoration	Restoration Ecology	2016
53	Wang, F.; Zhu, W.; Chen, H.	Changes of soil C stocks and stability after 70-year afforestation in the Northeast USA	Plant and Soil	2016
54	Wang, K.; Deng, L.; Ren, Z.; Shi, W.; Chen, Y.; Shang-Guan, Z.	Dynamics of ecosystem carbon stocks during vegetation restoration on the Loess Plateau of China	Journal of Arid Land	2016
55	Cai, H.; Di, X.; Chang, S.X.; Wang, C.; Shi, B.; Geng, P.; Jin, G.	Carbon storage, net primary production, and net ecosystem production in four major temperate forest types in northeastern China	Canadian Journal of Forest Research	2015
56	Robinson, S. J. B.; van den Berg, E.; Meirelles, G.S.; Ostle, N.	Factors influencing early secondary succession and ecosystem carbon stocks in Brazilian Atlantic Forest	Biodiversity and Conservation	2015
57	Cui, G.; Chen, Y.; Cao, Y.	Temporal-spatial pattern of carbon stocks in forest ecosystems in Shaanxi, Northwest China	PLoS ONE	2015
58	Ferez, A.P.C.; Campoe, O.C.; Mendes, J.C.T.; Stape, J.L.	Silvicultural opportunities for increasing carbon stock in restoration of Atlantic forests in Brazil	Forest Ecology and Management	2015
59	Forbes, A.S.; Norton, D.A.; Carswell, F.E.	Underplanting degraded exotic Pinus with indigenous conifers assists forest restoration	Ecological Management and Restoration	2015
60	Li, Y.; Zhao, X.; Wang, S.; Zhang, F.; Lian, J.; Huang, W.; Mao, W.	Carbon accumulation in the bulk soil and different soil fractions during the rehabilitation of desertified grassland in horqin sandy land (Northern China)	Polish Journal of Ecology	2015
61	McNicol, I.M.; Ryan, C.M.; Williams, M.	How resilient are African woodlands to disturbance from shifting cultivation?	Ecological Applications	2015
62	Xiao, X.; Wei, X.; Liu, Y.; Ouyang, X.; Li, Q.; Ning, J.	Aerial seeding: An effective forest restoration method in highly degraded forest landscapes of sub-tropic regions	Forests	2015
63	Zhang, Y.; Guo, S.; Liu, Q.; Jiang, J.; Wang, R.; Li, N.	Responses of soil respiration to land use conversions in degraded	Ecological Engineering	2015

		ecosystem of the semi-arid Loess Plateau		
64	Zhao, Y.G.; Liu, X.F.; Wang, Z.L.; Zhao, S.W.	Soil organic carbon fractions and sequestration across a 150-yr secondary forest chronosequence on the Loess Plateau, China	Catena	2015
65	Bôas, R. V.; Botelho, S. A.; Mello, J. M. de; Silva, C. A.	Spatial analysis and quantification of carbon stock in the forest ecosystems in restoration process (Minas Gerais State, Brazil)	Australian Journal of Basic and Applied Sciences	2014
66	Chen, X.B.; Zheng, H.; Zhang, W.; He, X.Y.; Li, L.; Wu, J.S.; Huang, D.Y.; Su, Y.R.	Effects of land cover on soil organic carbon stock in a karst landscape with discontinuous soil distribution	Journal of Mountain Science	2014
67	Ma, W.; Liu, Y.-H.; Sun, Y.-J.; Grabosky, J.	Carbon stock in Korean larch plantations along a chronosequence in the Lesser Khingan Mountains, China	Journal of Forestry Research	2014
68	Marton, J.M.; Fennessy, M.S.; Craft, C.B.	USDA conservation practices increase carbon storage and water quality improvement functions: An example from Ohio	Restoration Ecology	2014
69	Qi, X.; Wang, K.; Zhang, C.; Chen, H.; Zhang, W.	Effects of the implementation of ecological restoration policies on soil organic carbon storage in a discontinuous soil region	Acta Agriculturae Scandinavica	2014
70	Qin, Y.; Xin, Z.; Yu, X.; Xiao, Y.	Influence of vegetation restoration on topsoil organic carbon in a small catchment of the loess hilly region, China	PLoS ONE	2014
71	Samuelson, L.J.; Stokes, T.A.; Butnor, J.R.; Johnsen, K.H.; Gonzalez-Benecke, C.A.; Anderson, P.; Jackson, J.; Ferrari, L.; Martin, T.A.; Cropper, Jr. W.P.	Ecosystem carbon stocks in Pinus palustris forests	Canadian Journal of Forest Research	2014
72	Thi, T.H.D.; Huu, T.D.	Biomass and carbon stocks of the natural forests at Me Linh biodiversity station, Vinh Phuc province, Vietnam	Journal of Vietnamese Environment	2014
73	Zeng, X.; Zhang, W.; Cao, J.; Liu, X.; Shen, H.; Zhao, X.	Changes in soil organic carbon, nitrogen, phosphorus, and bulk density after afforestation of the "Beijing-Tianjin Sandstorm Source Control" program in China	Catena	2014
74	Arnalds, O.; Orradottir, B.; Aradottir, A.L.	Carbon accumulation in Icelandic desert Andosols during early stages of restoration	Geoderma	2013
75	Collard, S.; Fisher, A.; Hobbs, T.; Neumann, C.	Indicators of biodiversity and carbon storage in remnant and planted vegetation in the Mount Lofty Ranges of South Australia: lessons for biodiverse plantings	Ecological Management & Restoration	2013
76	Deng, L.; Shangguan, Z.P.	Carbon storage dynamics through forest restoration from 1999 to 2009 in China: A case study in Shaanxi province	Journal of Food, Agriculture and Environment	2013
77	Deng, L.; Wang, K.B.; Chen, M.L.; Shangguan, Z.P.; Sweeney, S.	Soil organic carbon storage capacity positively related to forest succession on the Loess Plateau, China	Catena	2013
78	Ekta Bhalla; Gupta, S.R.	The role of forestry plantations in soil carbon sequestration in a reserved forest in North-Western India	American-Eurasian Journal of Agricultural &	2013

			Environmental Sciences	
79	van der Vyver, M.L.; Cowling, R.M.; Mills, A.J.; Difford, M.	Spontaneous return of biodiversity in restored subtropical thicket: Portulacaria afra as an ecosystem engineer	Restoration Ecology	2013
80	Van Rooyen, M.W.; Van Rooyen, N.; Stoffberg, G.H.	Carbon sequestration potential of post-mining reforestation activities on the KwaZulu-Natal coast, South Africa	Forestry	2013
81	Wei, X.; Li, Q.; Liu, Y.; Liu, S.; Guo, X.; Zhang, L.; Niu, D.; Zhang, W.	Restoring ecosystem carbon sequestration through afforestation: A sub-tropic restoration case study	Forest Ecology and Management	2013
82	Zhang, Y.; Gu, F.; Liu, S.; Liu, Y.; Li, C.	Variations of carbon stock with forest types in subalpine region of southwestern China	Forest Ecology and Management	2013
83	Carswell,F.E.; Burrows, L.E.; Hall, G.M.J.; Mason, N.W.H.; Allen, R.B.	Carbon and plant diversity gain during 200 years of woody succession in lowland New Zealand	New Zealand Journal of Ecology	2012
84	Donato, D.C.; Kauffman, J.B.; Mackenzie, R.A.; Ainsworth, A.; Pfleeger, A.Z.	Whole-island carbon stocks in the tropical Pacific: implications for mangrove conservation and upland restoration	Journal of Environmental Management	2012
85	Gough, C.M.; Elliott, H.L.	Lawn soil carbon storage in abandoned residential properties: An examination of ecosystem structure and function following partial human-natural decoupling	Journal of Environmental Management	2012
86	Harper, R.J.; Okom, A.E.A.; Stilwell, A.T.; Tibbett, M.; Dean, C.; George, S.J.; Sochacki, S.J.; Mitchell, C.D.; Mann, S.S.; Dods, K.	Reforesting degraded agricultural landscapes with Eucalypts effects on carbon storage and soil fertility after 26 years	Agriculture, Ecosystems and Environment	2012
87	Liu, Y.; Zhang, Y.; Liu, S.	Aboveground carbon stock evaluation with different restoration approaches using tree ring chronosequences in Southwest China	Forest Ecology and Management	2012
88	Mosquera, O.; Buurman, P.; Ramirez, B.L.; Amezquita, M.C.	Carbon replacement and stability changes in short-term silvo-pastoral experiments in Colombian Amazonia	Geoderma	2012
89	Rheinhardt, R.D.; Brinson, M.M.; Meyer, G.F.; Miller, K.H.	Carbon storage of headwater riparian zones in an agricultural landscape	Carbon Balance and Management	2012
90	Yao, J.; Murray, D.B.; Adhikari, A.; White, J.D.	Fire in a sub-humid woodland: The balance of carbon sequestration and habitat conservation	Forest Ecology and Management	2012
91	Aoyama, K.; Yoshida, T.; Harada, A.; Noguchi, M.; Miya, H.; Shibata, H.	Changes in carbon stock following soil scarification of non-wooded stands in Hokkaido, northern Japan	Journal of Forest Research	2011
92	Celentano, D.; Zahawi, R.A.; Finegan, B.; Casanoves, F.; Ostertag, R.; Cole, R.J.; Holl, K.D.	Tropical forest restoration in Costa Rica: The effect of several strategies on litter production, accumulation and decomposition [Restauración ecológica de bosques tropicales en Costa Rica: Efecto de varios modelos en la producción, acumulación y descomposición de hojarasca]	Revista de Biologia Tropical	2011
93	Collins, B.M.; Everett, R.G.; Stephens, S.L.	Impacts of fire exclusion and recent managed fire on forest structure in old growth Sierra Nevada mixed-conifer forests	Ecosphere	2011

94	Liu, Y.; Wang, Q.; Yu, G.; Zhu, X.; Zhan, X.; Guo, Q.; Yang, H.; Li, S.; Hu, Z.	Ecosystems carbon storage and carbon sequestration potential of two main tree species for the Grain for Green Project on China's hilly Loess Plateau	Shengtai Xuebao/ Acta Ecologica Sinica	2011
95	Owari, T.; Kamata, N.; Tange, T.; Kaji, M.; Shimomura, A.	Effects of silviculture treatments in a hurricane-damaged forest on carbon storage and emissions in central Hokkaido, Japan	Journal of Forestry Research	2011
96	Rodrigues Nogueira, Jr.; de Moraes Gonçalves, J.L.; Lex Engel, V.; Parrotta, J.	Soil dynamics and carbon stocks 10 years after restoration of degraded land using Atlantic forest tree species [Dinámica del suelo y estoque de carbono después de diez años de la restauración de tierras degradadas usando especies arbóreas del bosque atlántico]	Investigacion Agraria Sistemas y Recursos Forestales	2011
97	Sorensen, C.D.; Finkral, A.J.; Kolb, T.E.; Huang, C.H.	Short- and long-term effects of thinning and prescribed fire on carbon stocks in ponderosa pine stands in northern Arizona	Forest Ecology and Management	2011
98	Chen, F.S.; Zeng, D.H.; Fahey, T.J.; Liao, P.F.	Organic carbon in soil physical fractions under different-aged plantations of Mongolian pine in semi-arid region of Northeast China	Applied Soil Ecology	2010
99	Dore, S.; Kolb, T.E.; Montes-Helu, M.; Eckert, S.E.; Sullivan, B.W.; Hungate, B.A.; Kaye, J.P.; Hart, S.C.; Koch, G.W.; Finkral, A.	Carbon and water fluxes from ponderosa pine forests disturbed by wildfire and thinning	Ecological Applications	2010
100	Gamboa, A.M.; Hidalgo, C.; De León, F.; Etchevers, J.D.; Gallardo, J.F.; Campo, J.	Nutrient addition differentially affects soil carbon sequestration in secondary tropical dry forests: early- versus late-succession stages	Restoration Ecology	2010
101	Kanowski, J.; Catterall, C.P.	Carbon stocks in above-ground biomass of monoculture plantations, mixed species plantations and environmental restoration plantings in north-east Australia	Ecological Management and Restoration	2010
102	Kalinina, O.; Goryachkin, S.V.; Karavaeva, N.A.; Lyuri, D.I.; Najdenko, L.; Giani, L.	Self-restoration of post-agrogenic sandy soils in the southern Taiga of Russia: Soil development, nutrient status, and carbon dynamics	Geoderma	2009
103	Finkral, A.J.; Evans, A.M.	The effects of a thinning treatment on carbon stocks in a northern Arizona ponderosa pine forest	Forest Ecology and Management	2008
104	Fonseca, G.; W.; Alice, F. E.; Montero,J.; Toruño, H.; Leblanc, H.	Biomass and carbon accumulation in secondary forests and forestry plantations as restoration tools in the Caribbean zone of Costa Rica	Agroforestería en las Américas	2008
105	Zheng, H.; Ouyang, Z.; Xu, W.; Wang, X.; Miao, H.; Li, X.; Tian, Y.	Variation of carbon storage by different reforestation types in the hilly red soil region of southern China	Forest Ecology and Management	2008
106	Mills, A.J.; Cowling, R.M.	Rate of carbon sequestration at two thicket restoration sites in the Eastern Cape, South Africa	Restoration Ecology	2006
107	Laclau P.	Biomass and carbon sequestration of ponderosa pine plantations and native cypress forests in northwest Patagonia	Forest Ecology and Management	2003

Appendix I. Location of plots installed in Anhembi. Each sample point represents one plot.



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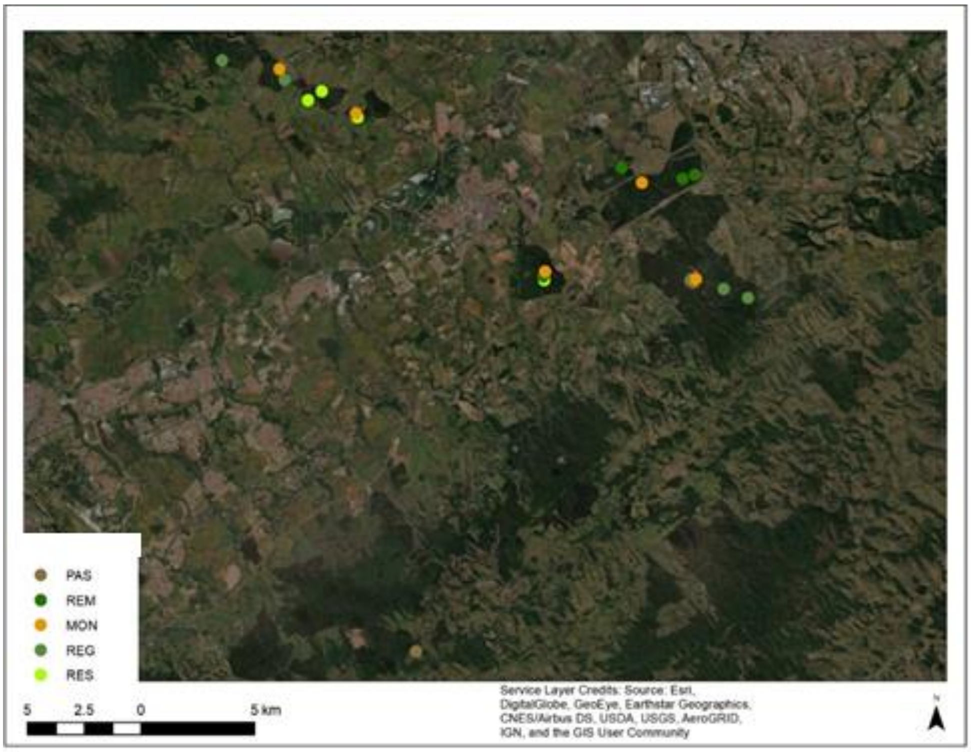
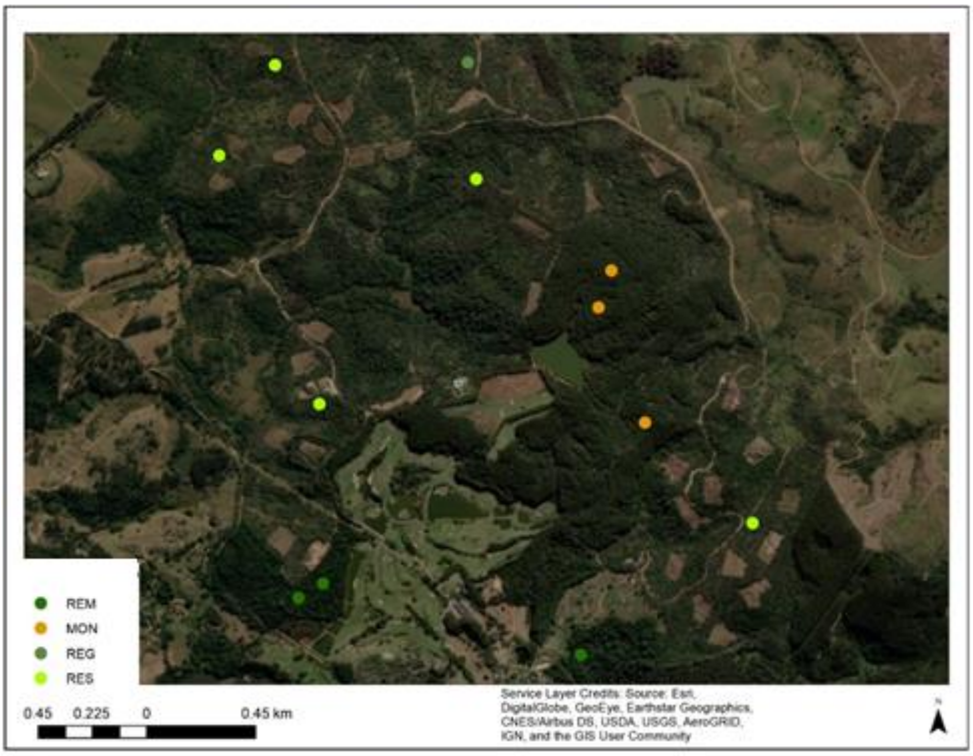
Appendix J. Location of plots installed in Caçapava. Each sample point represents one plot.



Appendix K. Location of plots installed in Campinas. Each sample point represents one plot.



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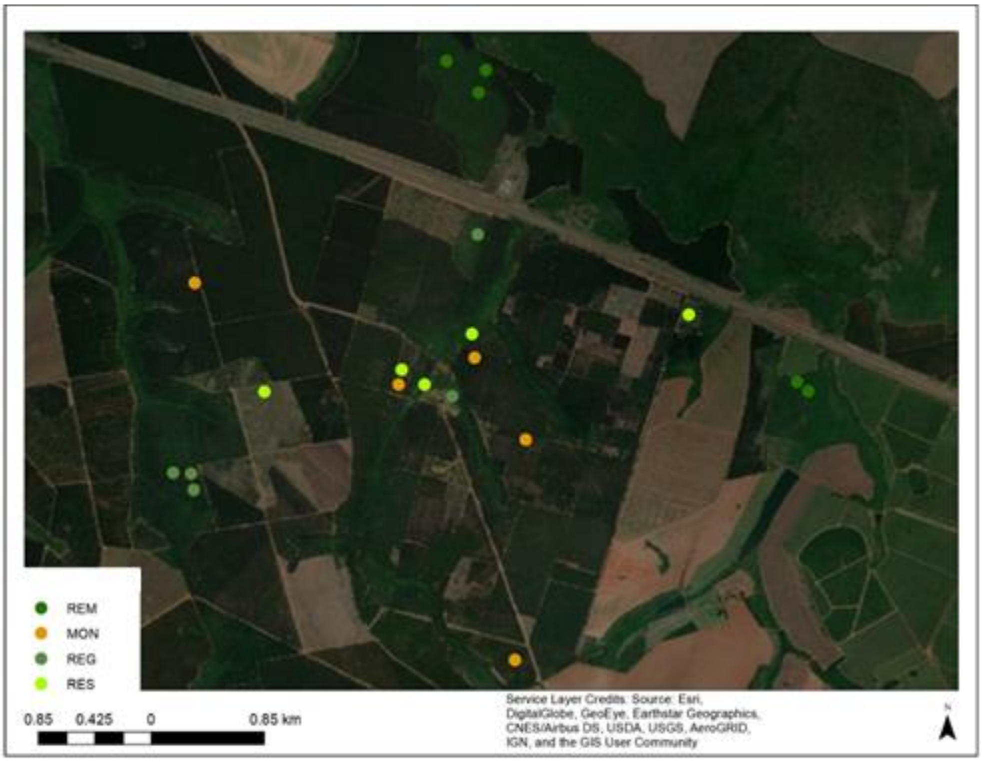
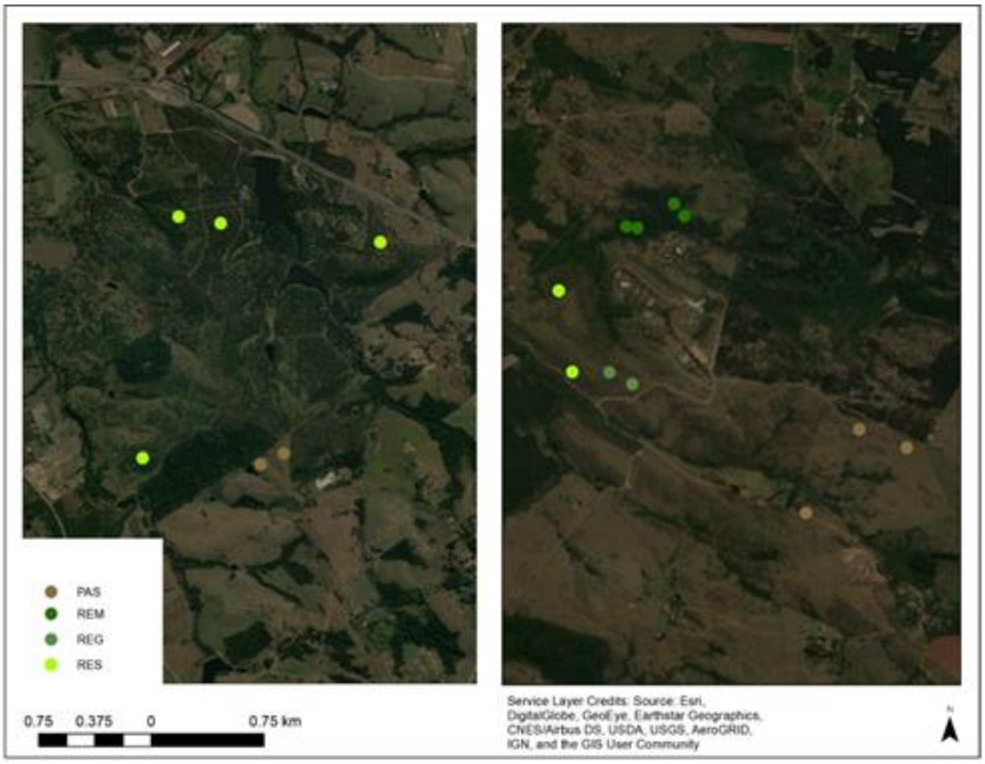
Appendix L. Location of plots installed in Itatinga. Each sample point represents one plot.



Appendix M. Location of plots installed in Itu. Each sample point represents one plot.



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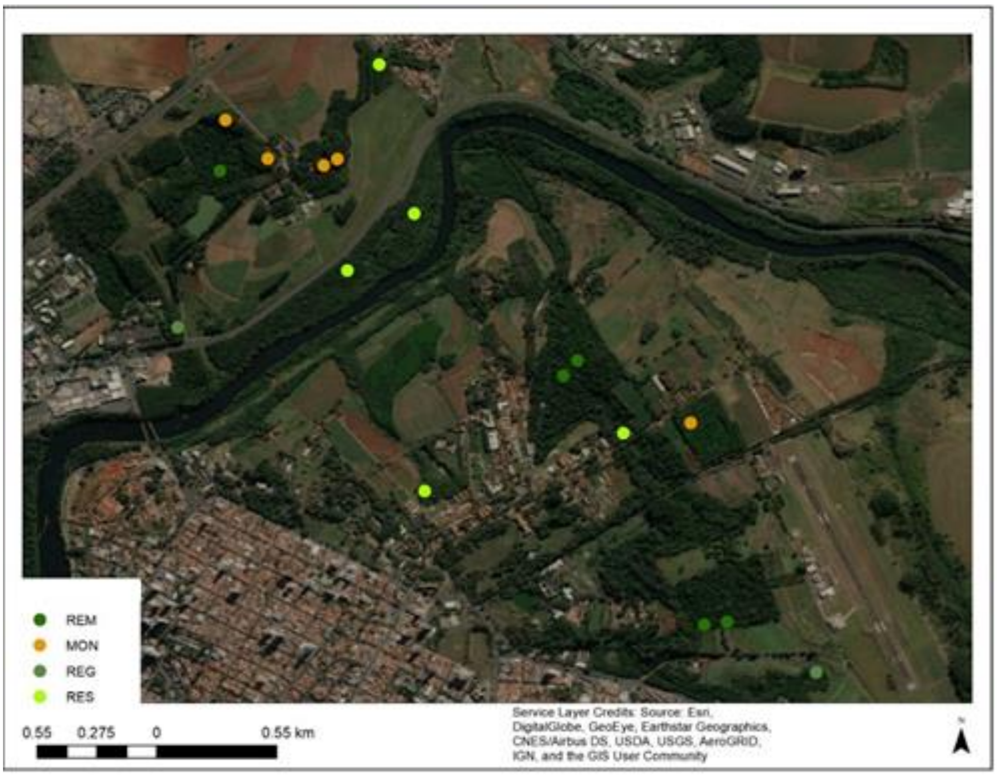
Appendix N. Location of plots installed in Piracicaba. Each sample point represents one plot.



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Appendix O. Information on plots allocated across the six study sites.

Code	Local	Soil use	Abundance (nº ind)	Diversity	Richness (Number of sp.)	Wood density (g cm^{-3})	Large diameter (nº ind)	Medium diameter (nº ind)	Small diameter (nº ind)	Age (year)	Soil density (g cm^{-3})
ANH_14	Anhembi	MONO	73	0,00	1	0,83	32	41	0	10	1,48
ANH_19	Anhembi	MONO	135	0,00	1	0,83	86	49	0	14	1,47
ANH_23	Anhembi	MONO	146	0,17	2	0,49	46	100	0	14	1,48
ANH_55	Anhembi	MONO	71	0,55	2	0,74	31	40	0	9	1,14
ANH_80	Anhembi	MONO	46	0,00	1	0,53	9	26	11	22	1,61
ARE_01	Piracicaba	MONO	84	0,00	1	0,65	28	53	3	20	3,89
ARE_14	Piracicaba	MONO	55	0,00	1	0,65	5	46	4	15	1,57
ARE_15	Piracicaba	MONO	137	0,00	1	0,65	58	78	1	12	1,43
ARE_16	Piracicaba	MONO	29	0,14	2	0,82	2	20	7	23	1,66
CAC_17	Caçapava	MONO	121	0,00	1	0,83	121	0	0	13	1,02
CAC_24	Caçapava	MONO	119	0,00	1	0,83	119	0	0	18	1,25
CAV_01	Caçapava	MONO	108	0,09	1	0,83	78	30	0	15	1,43
CAV_02	Caçapava	MONO	112	0,00	1	0,83	112	0	0	13	1,13
CAV_03	Caçapava	MONO	98	0,00	1	0,83	97	1	0	13	1,21
ESA_04	Piracicaba	MONO	40	0,00	1	0,65	1	37	2	16	1,07
GUA_19	Campinas	MONO	174	1,06	9	0,47	68	90	16	< 35	1,27
GUA_20	Campinas	MONO	166	2,17	11	0,52	60	62	44	< 35	1,18
GUA_21	Campinas	MONO	126	1,74	12	0,38	80	26	20	< 35	1,38
ITA_09	Itatinga	MONO	160	0,11	2	0,66	88	72	0	23	1,84
ITA_24	Itatinga	MONO	57	0,17	3	0,83	4	44	9	19	1,52
ITA_41	Itatinga	MONO	138	0,08	3	0,83	84	54	0	14	1,31
ITA_55	Itatinga	MONO	79	0,00	1	0,83	18	61	0	8	1,24
ITA_56	Itatinga	MONO	159	0,10	3	0,83	125	34	0	16	1,33
ANH_64	Anhembi	PAST	38	1,31	4	0,50	35	3	0	< 35	1,74
ANH_65	Anhembi	PAST	1	0,00	0	0,65	1	0	0	< 35	1,63
ANH_66	Anhembi	PAST	39	0,00	1	0,53	39	0	0	< 35	1,58
ANH_71	Anhembi	PAST	0	0,00	0	0,00	0	0	0	< 35	1,43
ANH_76	Anhembi	PAST	0	0,00	0	0,00	0	0	0	< 35	1,51
CAV_12	Caçapava	PAST	0	0,00	0	0,00	0	0	0	8	1,57
CAV_15	Caçapava	PAST	0	0,00	0	0,00	0	0	0	8	1,61
CAV_16	Caçapava	PAST	0	0,00	0	0,00	0	0	0	8	1,56
ESA_32	Piracicaba	PAST	0	0,00	0	0,00	0	0	0	S/N	3,24
ESA_33	Piracicaba	PAST	0	0,00	0	0,00	0	0	0	S/N	1,60
ESA_34	Piracicaba	PAST	0	0,00	0	0,00	0	0	0	S/N	1,50
ESA_40	Piracicaba	PAST	0	0,00	0	0,00	0	0	0	S/N	1,38
ESA_41	Piracicaba	PAST	0	0,00	0	0,00	0	0	0	S/N	1,48
ITU_03	Itu	PAST	0	0,00	0	0,00	0	0	0	< 35	1,43
ITU_04	Itu	PAST	0	0,00	0	0,00	0	0	0	< 35	1,39
ITU_05	Itu	PAST	0	0,00	0	0,00	0	0	0	< 35	1,43
ITU_42	Itu	PAST	0	0,00	0	0,00	0	0	0	< 35	1,37
ITU_44	Itu	PAST	0	0,00	0	0,00	0	0	0	< 35	1,27
JAM_07	Caçapava	PAST	0	0,00	0	0,00	0	0	0	< 35	1,34
ANH_31	Anhembi	REG	132	1,66	12	0,68	108	21	3	< 35	1,04
ANH_40	Anhembi	REG	91	2,19	14	0,63	68	19	4	< 35	1,04
ANH_47	Anhembi	REG	90	1,34	8	0,69	72	17	1	< 35	1,18
ANH_62	Anhembi	REG	110	1,27	10	0,75	82	28	0	< 35	1,41
ANH_72	Anhembi	REG	159	0,88	15	0,68	147	12	0	< 35	1,77
ARE_02	Piracicaba	REG	100	3,04	26	0,62	62	26	12	18	1,10
CAC_21	Caçapava	REG	155	2,51	27	0,60	128	27	0	18	1,10
CAC_22	Caçapava	REG	313	1,71	19	0,69	303	10	0	13	1,10
CAV_07	Caçapava	REG	99	2,80	22	0,65	83	15	1	13	1,38
CAV_08	Caçapava	REG	110	2,79	24	0,61	87	20	3	13	1,13
ESA_18	Piracicaba	REG	139	1,84	14	0,56	115	23	1	10	1,31
GUA_04	Campinas	REG	378	2,29	27	0,64	310	68	0	< 35	1,45
GUA_05	Campinas	REG	300	2,68	31	0,61	240	58	2	< 35	1,04

GUA_09	Campinas	REG	129	2,12	14	0,55	93	35	1	13	1,34
ITA_27	Itatinga	REG	116	2,52	21	0,67	87	26	3	17	1,49
ITA_32	Itatinga	REG	119	2,38	22	0,63	109	10	0	35	1,02
ITA_33	Itatinga	REG	140	2,30	21	0,63	127	13	0	35	1,85
ITA_34	Itatinga	REG	182	2,92	32	0,63	169	12	1	35	1,51
ITA_51	Itatinga	REG	192	2,25	26	0,66	183	9	0	35	1,04
ITU_19	Itu	REG	0	0,00	0	0,56	0	0	0	7	1,40
ITU_20	Itu	REG	10	1,35	5	0,57	10	0	0	7	1,44
ITU_21	Itu	REG	31	0,66	2	0,00	30	1	0	7	1,41
ANH_74	Anhembi	REM	140	2,68	21	0,67	103	28	9	< 35	1,08
ANH_75	Anhembi	REM	190	2,26	22	0,73	173	14	3	< 35	1,34
ARE_05	Piracicaba	REM	77	1,77	12	0,75	52	21	4	< 35	1,16
CAV_10	Caçapava	REM	155	0,00	29	0,68	119	32	4	< 35	1,25
CAV_11	Caçapava	REM	165	2,06	25	0,48	123	33	9	< 35	0,73
CAV_13	Caçapava	REM	137	3,03	35	0,63	113	19	5	< 35	1,34
CAV_14	Caçapava	REM	125	2,39	20	0,64	97	24	4	< 35	0,91
ESA_09	Piracicaba	REM	78	1,99	13	0,66	45	27	6	< 35	1,47
ESA_24	Piracicaba	REM	93	2,34	18	0,64	79	12	2	< 35	0,60
ESA_25	Piracicaba	REM	96	2,01	19	0,58	71	24	1	< 35	1,01
ESA_27	Piracicaba	REM	105	2,34	19	0,55	75	28	2	< 35	1,03
GUA_22	Campinas	REM	126	2,71	23	0,74	93	31	2	< 35	1,21
GUA_23	Campinas	REM	218	2,45	19	0,86	150	60	8	< 35	1,24
GUA_24	Campinas	REM	162	2,49	19	0,83	106	34	22	< 35	1,13
ITA_48	Itatinga	REM	99	3,19	35	0,68	63	31	5	< 35	0,90
ITA_49	Itatinga	REM	86	2,72	24	0,65	57	19	10	< 35	1,12
ITA_50	Itatinga	REM	94	3,28	36	0,59	66	25	3	< 35	0,77
ITA_61	Itatinga	REM	150	2,51	26	0,58	96	50	4	< 35	1,05
ITA_62	Itatinga	REM	189	2,68	28	0,68	150	39	0	< 35	0,89
ITU_09	Itu	REM	76	2,14	15	0,73	57	19	0	< 35	1,27
ITU_10	Itu	REM	72	2,62	17	0,75	46	24	2	< 35	1,22
ITU_11	Itu	REM	81	1,92	10	0,65	70	10	1	< 35	1,20
ITU_12	Itu	REM	68	2,17	13	0,55	56	11	1	< 35	1,28
ITU_38	Itu	REM	59	1,54	8	0,61	57	2	0	< 35	1,29
ANH_35	Anhembi	REST	84	2,34	17	0,71	62	20	2	16	1,12
ANH_49	Anhembi	REST	155	2,04	13	0,67	132	23	0	11	1,16
ANH_51	Anhembi	REST	165	2,95	35	0,57	122	42	1	17	1,10
ANH_57	Anhembi	REST	132	2,55	17	0,61	103	24	5	19	1,54
ANH_60	Anhembi	REST	231	3,19	35	0,71	59	127	45	8	1,57
ARE_08	Piracicaba	REST	123	3,05	30	0,63	89	30	4	16	1,66
CAC_18	Caçapava	REST	160	2,22	20	0,60	135	25	0	13	1,15
CAC_19	Caçapava	REST	170	2,56	22	0,63	152	18	0	13	1,24
CAC_20	Caçapava	REST	206	2,36	24	0,64	174	32	0	13	1,17
CAV_09	Caçapava	REST	116	2,81	25	0,61	92	24	0	11	1,34
ESA_01	Piracicaba	REST	144	3,49	46	0,63	100	37	7	17	1,39
ESA_07	Piracicaba	REST	149	1,25	10	0,63	96	53	0	18	1,53
ESA_21	Piracicaba	REST	159	2,72	20	0,67	105	46	8	18	1,51
ESA_23	Piracicaba	REST	153	2,08	21	0,61	116	35	2	18	1,55
GUA_06	Campinas	REST	171	2,90	24	0,65	124	45	2	15	1,57
GUA_07	Campinas	REST	239	2,11	16	0,63	188	49	2	13	1,34
GUA_11	Campinas	REST	220	2,63	20	0,61	160	58	2	13	1,31
GUA_12	Campinas	REST	200	2,43	19	0,68	184	16	0	11	1,24
GUA_15	Campinas	REST	280	2,74	24	0,59	206	74	0	12	1,35
ITA_28	Itatinga	REST	161	3,06	32	0,65	120	34	7	23	1,57
ITA_29	Itatinga	REST	145	3,20	34	0,62	113	26	6	18	1,30
ITA_31	Itatinga	REST	104	1,90	13	0,59	90	14	0	16	1,58
ITA_36	Itatinga	REST	170	1,59	9	0,59	170	0	0	6	1,54
ITA_42	Itatinga	REST	105	1,96	11	0,63	86	19	0	8	1,66
ITU_15	Itu	REST	144	1,89	13	0,56	134	10	0	8	1,46
ITU_17	Itu	REST	168	1,78	13	0,59	157	11	0	8	1,36

ITU_24	Itu	REST	50	2,02	10	0,79	34	16	0	13	1,17
ITU_28	Itu	REST	66	1,69	8	0,52	56	10	0	12	1,15
ITU_34	Itu	REST	123	2,01	17	0,58	83	38	2	15	1,18