Catalina Zuluaga Rodríguez

Estoque de carbono e provisão de papel em paisagens de floresta e plantações de Eucalipto: estimativa de dados, trade-offs e potenciais cenários

Carbon stock and paper provision in landscapes with forest and Eucalyptus plantations: data estimates, trade-offs and possible scenarios

São Paulo

2020

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Tese apresentada ao Instituto de Biociências da Universidade de São Paulo, para a obtenção de Título de Doutor em Ciências, na Área de Ecologia.

Orientadora: Rozely Ferreira Dos Santos

São Paulo

2020

Ficha Catalográfica

Zuluaga, Catalina

Estoque de carbono e provisão de papel em paisagens de floresta e plantações de Eucalipto: estimativa de dados, trade-offs, potenciais cenários.

129 páginas.

Tese - Instituto de Biociências da Universidade de São Paulo. Departamento de Ecologia.

1. Estimativas de biomassa, 2. Regulação climática, 3 Corte de silvicultura, 4. Trade-offs I. Universidade de São Paulo. Instituto de Biociências. Departamento de Ecologia.

Comissão Julgadora:

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Prof(a). Dr(a). Prof(a). Dr(a).

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Prof(a). Dr(a). Profa. Dra.

Orientadora

Agradecimentos

Agradeço primeiramente a minha família por apoiar-me na ideia louca de sair da zona do conhecido para estudar em outro país longe deles, buscando crescimento personal e professional. Apesar do sacrifício que isso implicava e ainda implica, eles sempre estiveram aí para me reconfortar.

Agradeço à professora Rozely me aceitar como orientanda ainda sem me-conhecer e por todas as oportunidades de crescimento profissional e pessoal que propiciou ao longo de estes 4 anos. A Jean Paul Metzger e Fábio Scarano, membros do meu comitê de acompanhamento, por me apoiar na construção da tese. A Vânia, Jomar e Paulo Inácio pela avaliação crítica, objetiva e profissional de minha qualificação. A Glauco pelo apoio em vários momentos.

A minhas amigas e amigos de sempre, aqueles com que apesar da distância mantemos relacionamento intacto de parceria, apoio e interesse mútuo. Agradeço a novos amigas e amigos que já não são tão novos assim, por fazer este caminho mais leve. A colegas e companheiros de luta na pós-graduação que me proporcionaram e continuam proporcionando aprendizados, motivação e admiração. Em especial a aqueles que me ajudaram no trabalho de campo, com sugestões para melhorar o trabalho e com revisões do texto final da qualificação e da tese.

A Vera, Wellington e Valmir cuja entrega e dedicação ao serviço implicou em uma ajuda inestimável para mim em diversos momentos.

A German pela inspiração, o apoio, a motivação, a ajuda, por crer em mim e me-levantar quantas vezes foi necessário e por tantas outras coisas.

A BRASIL por me-receber e me-acolher e pelo financiamento através da CAPES já que o presente trabalho foi realizado com apoio da Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Código de Financiamento 001.

A National Geographic Society pela ajuda financeira para a realização do trabalho de campo.

Agradezco en primer lugar a mi familia por apoyarme en esa idea loca de salir de la zona de lo conocido para estudiar en otro país, lejos de ellos, en busca de crecimiento personal y profesional. A pesar del sacrificio que eso implicaba y sigue implicando por estar separados, ellos siempre han estado ahí para reconfortarme.

A la profesora Rozely por aceptar orientarme sin conocerme y por todas las oportunidades de crecimiento profesional y personal que propició a lo largo de estos 4 años. A Jean Paul Metzger y Fabio Scarano, miembros de mi comité de acompañamiento, por apoyar en la construcción de la tesis. A Vania, Jomar y Paulo Ignacio por su evaluación crítica, objetiva y profesional de mi calificación. A Glauco por el apoyo en vários momentos.

A amigos y amigas de siempre con quienes a pesar de la distancia mantenemos relación intacta de parceria, apoyo e interés mutuo. A amigas y amigos nuevos que ya no son tan nuevos, por hacer el camino más leve. A colegas y compañeros de lucha que me brindaron y seguirán brindando aprendizaje, motivación y admiración. En especial a quienes me ayudaron en el trabajo de campo, con sugerencias para mejorar el trabajo o en revisiones de texto de la calificación o de la tesis.

A Vera, Wellington y Valmir cuya entrega y dedicación al trabajo implicó en una ayuda invaluable para mí en vários momentos.

A German por inspirarme, apoyarme, motivarme, levantarme, ayudarme a creer y por otras tantas cosas.

A BRASIL por recibirme y acogerme y através de CAPES permitir dedicarme exclusivamente a mis responsabilidades del doctorado.

A National Geographic Society por la ayuda financiera para la realización de mi trabajo de campo.

Sumário

Apresentação

Em diversas partes do mundo as atividades humanas vêm, cada vez mais, se apoderando dos espaços que eram originalmente ocupados pela vegetação natural, gerando constantes mudanças de uso da terra, resultando em perda de biodiversidade, perda de habitats, extinção de espécies, redução dos estoques de recursos naturais, incremento das mudanças climáticas, entre outras consequências (Batlle-Bayer et al. 2010; Jantz et al. 2014; Balthazar et al. 2015). O desmatamento contínuo impacta negativamente a capacidade dos ecossistemas naturais de atuar como sumidouros de carbono uma vez que a função ecológica de armazená-lo a partir do crescimento vegetal não compensa a perda de carbono pelo desmatamento e por perturbações dentro da floresta em pé (Baccini et al. 2017). A função ecológica, que contribui para a mitigação da mudança climática, é reconhecida como serviço ecossistêmico de regulação climática global (SERCG), segundo CICES - Classificação Internacional Comum dos Serviços Ecossistêmicos (Haines-young and Potschin 2018). A redução da oferta do SERCG pela perda de floresta implica na diminuição do sequestro de carbono na atmosfera e, consequentemente, no agravamento da mudança do clima.

Muitas vezes a justificativa para as mudanças no uso da terra em sistemas naturais é que há um substancial incremento econômico nessas alterações (Brockerhoff et al. 2013), levando ao desenvolvimento da nação e ao bem-estar humano. Essas mudanças na terra são feitas para a obtenção de produtos como alimento e materiais. Esta condição é considerada como serviço ecossistêmico de provisão (MEA 2005; Haines-young and Potschin 2018). A ocorrência de vários serviços ecossistêmicos num mesmo local resulta em dinâmicas complexas que implicam em relações positivas, negativas e neutras. Os resultados de pesquisas que avaliam as relações entre serviços ecossistêmicos são variáveis e ás vezes contraditórios (Geneletti et al. 2018; Lin et al. 2018). Sob essa perspectiva, a grande responsabilidade de planejadores da paisagem e tomadores de decisão é avaliar e gerenciar os diferentes serviços dos ecossistemas em paisagens espacialmente heterogêneas para garantir a sustentabilidade da paisagem (Turner et al. 2011; Farley 2012; Wu 2013; Cavender-bares et al. 2015; Xiangzheng et al. 2016).

O desafio aumenta quando consideramos que as relações entre serviços devem ser observadas através de diferentes escalas, sejam relativas à extensão territorial ou temporal (Qiao et al. 2019). Quantificar e avaliar as escalas temporais e espaciais nos trade-offs entre serviços ecossistêmicos é favorável para o manejo de ecossistemas (Qiao et al. 2019), assim como avaliar a potencialidade da paisagem em continuar fornecendo diferentes serviços para propor opções de manejo, conduzindo progressivamente à sustentabilidade ambiental (Schröter et al. 2014). Um planejador deve reconhecer as variações no tempo e definir o patamar de tolerância para mudanças em uma paisagem, de forma a manter o balanço adequado entre serviços ecossistêmicos no futuro, garantindo o bem-estar humano. Em outras palavras, é desejável encontrar um padrão de cobertura e uso da terra numa paisagem que garanta a continuidade de processos ecológicos ao longo do tempo, antes que cesse a oferta de serviços (Farley 2012; Adams 2014). Assim, consideramos vital apontar prováveis limiares e trade-offs entre serviços, que possam indicar os limites de uso humano. Essa resposta só será efetiva se optarmos por metodologias apropriadas considerando a extensão espacial assim como, a formulação de diferentes cenários em escalas temporais relevantes de acordo com os serviços que estejam sendo avaliados. Sob essas considerações, nosso objetivo geral foi: (a) avaliar as possíveis diferenças nos valores de biomassa acima do solo a partir de: estimativas de campo e valores obtidos do Mapa Pantropical de densidade de biomassa. Assim mesmo, explorar possíveis causas que expliquem as diferenças nas estimativas. (b) Estimar o estoque de carbono em floresta natural e silvicultura de Eucalyptus assim como avaliar o estoque de carbono em bacias ocupadas por um gradiente entre floresta natural e silvicultura de Eucalyptus. (c) Identificar a relação entre os serviços de estoque de carbono e a provisão de papel em bacias ocupadas por um gradiente entre floresta natural e silvicultura de Eucalyptus e através de uma análise de cenários identificar mudanças na relação entre os dois serviços considerando o ciclo de corte da silvicultura para produção de papel.

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Chapter 1

Approaches on aboveground biomass estimates in a fragmented secondary forest: insights for environmental planning

Catalina Zuluaga Rodríguez, Susana López Caracena, Rozely Ferreira dos Santos

Abstract

Accurate estimates of forest aboveground biomass (AGB) are essential for improving carbon predictions that support public decisions regarding land-use-cover planning and ecosystem services provision. Furthermore, the AGB provides the base for international communication about the links between greenhouse gas emissions, carbon sequestration, deforestation, and forest degradation. Field-based estimates of AGB are useful to recognize local and detailed patterns but can be expensive and time-consuming, especially in steeply sloped landscapes. Instead, there are biomass maps but it use requires special care when the results are translated into environmental policies. Here we evaluate the possible differences between AGB values from the Pantropical Aboveground Biomass Density Map (PABDM) and field estimates in Atlantic Forest fragments. We explore the possible causes of the differences found between them and discuss the consequences for public policies and environmental planning. AGB estimates from PABDM maps are higher than field-based estimates in all levels tested. We call for policymakers to pay attention to the results since the decision could be very distinct if based on one or the other approach.

Keywords: Carbon stock, field estimates, Brazilian Atlantic forest, biomass density map, environmental planning.

Resumo

Estimativas precisas de biomassa acima de solo (BAS) são essenciais para melhorar as previsões sobre carbono e apoiar políticas públicas relacionadas com o planejamento do uso da terra e a provisão de serviços ecossistêmicos. Além disso, o conhecimento da BAS constitui a base para a comunicação internacional sobre gases de efeito estufa resultantes do desmatamento e da degradação florestal. Estimativas de BAS feitas no campo são importantes para reconhecer e detalhar padrões locais, mas podem ser custosas e consumir muito tempo, especialmente em paisagens muito declivosas. Por outro lado existem mapas de biomassa, mas seu uso requer atenção especial na hora de transladar traduzir os resultados para a criação de politicas públicas. Neste trabalho, nós avaliamos as possíveis diferencias entre valores de BAS provenientes do Mapa Pantropical de Densidade de Biomassa e de estimativas de campo em fragmentos de Mata Atlântica. Nós exploramos as possíveis causas das diferencias encontradas e discutimos as consequências para politicas publicas e planejamento ambiental. As estimativas de BAS baseadas no mapa foram entre 1.2 - 24 vezes maiores que as estimativas de campo. Nós chamamos a atenção dos tomadores de decisão para escolher cuidadosamente o método de avaliação de biomassa, já que os resultados entre métodos diferem substancialmente.

Palavras chave: Estoque de carbono, estimativas em campo, Mata Atlântica, Mapa de Densidade de Biomassa, planejamento ambiental.

Introduction

Biomass density estimates provide the means for calculating the amount of carbon dioxide that was removed from the atmosphere because carbon is approximately 50% of the total plant biomass (Shimamoto et al. 2014). Forest biomass is distributed in above and belowground living mass and dead plant mass such as fine litter and wood. The aboveground biomass (AGB) is relatively easy to measure, then AGB tends to be the best characterized (GOFC-GOLD 2009).

The reduction of the biomass as a result of forest conversion and land-use-cover change produces significant emissions of carbon to the atmosphere (Houghton et al. 2012). For example, in tropical forests deforestation accounts for around 10% of the annual global greenhouse gas emissions (IPCC 2014). Indeed, Baccini recently showed that tropical forests are becoming a net source of carbon due to biomass loss in response to disturbances (Baccini et al. 2017).

Recently, governments and scientists are looking for strategies to mitigate greenhouse gas emissions, particularly carbon dioxide by forest protection and restoration. In that context, monitoring AGB has important implications in economics, policy, and conservation (Gibbs et al. 2007), particularly in forest planning and conservation projects. Thus, AGB and changes in AGB must be estimated with confidence (Mitchard et al. 2014a). The selection of the AGB estimate method is critical and must consider the objectives, the spatial and temporal scales and the extension of the project.

On the one hand, the fieldwork makes possible the identification of signs of human drivers of AGB reduction as physical evidence of selective logging or understory fires. Such disturbances can account for additional biomass losses on the order of 47-75% of deforestation and recognize these drivers may help to understand the AGB found (Berenguer et al. 2014). However, fieldwork is expensive and time-consuming (Houghton et al. 2009). On the other hand, large-scale biomass maps produced using RS resources can provide spatially explicit estimates of biomass density to assist ecosystem management (Avitabile et al. 2016), covering continental or even worldwide scales (Eva et al. 2010). However, the results from RS products require special attention because sensor systems have different spatial, temporal, radiometric, and spectral resolutions, resulting in different advantages and disadvantages to AGB estimation (Lu 2006; Eisfelder et al. 2012). RS for forest AGB estimation depends on the cost-benefit relationship that includes image accessibility, availability of image processing techniques, and data confidence.

Integrative approaches between fieldwork and RS have been developed in the last decades leading to substantial progress in mapping broad-scale biomass (Asner et al. 2010; Saatchi et al. 2011; Baccini et al. 2012). Global maps are being intensely used, and currently became essential for decision making on ecosystem planning and management. Nonetheless, accurate maps are difficult to produce and uncertainties in biomass estimates are often large (Mitchard et al. 2013; Ometto et al. 2014).

Most of the maps have focused on regional or global scales which make them important tools for national communications to the United Nations Framework Convention on Climate Change (Englund et al. 2017). However, higher spatial resolution at the local scale is desirable to facilitate the development of successful resource management policies (Davies et al. 2011).

In Brazil, most of the biomass maps have focused on the Amazon biome, but information about other biomes as the Atlantic Forest is still scarce. Mapping approaches to build and validate the estimates, proceed from datasets outside of the local of interest (Robinson et al. 2009; Avitabile et al. 2016; Englund et al. 2017). Then, the use of an unsuitable map for landscape management can cause sudden great damage, since the maps have large differences, both in terms of biomass values and its spatial distribution (Englund et al. 2017).

The Pantropical Aboveground Biomass Density map (PABDM), launched in 2014 through the Global Forest Watch (GFW) platform, is widely used to provide baseline data for REDD (Mitchard et al. 2014a). However, the GFW platform warns that the PABDM provides more accurate estimates when aggregated in areas around higher than 5000 hectares (World Resources Institute 1997). Also, the authors of the map call for attention that the PABDM should be useful for local scales, but considering the lower accuracy at the pixel level (Baccini et al. 2012).

In a recent work, Mitchard (2014b) found that the PABDM fails to detect the existing gradient on AGB at the Amazon biome, but this situation tends to decrease when aggregating to country or biome scale (Mitchard et al. 2013). Would the PABDM detect the variation in AGB in fragmented landscapes such as the Brazilian Atlantic Forest biome?

In this context, our goal was to evaluate the possible differences between the AGB based in field estimates and the PAGDM in a fragmented tropical forest. We also aim to explore the causes of those differences between AGB estimates and to discuss the consequences of using these methods for taking decisions in forest landscape planning.

Methods

Study area

We studied remnants of the threatened Brazilian Atlantic Forest located in São Paulo, Brazil (Figure 1). Due to its steep and mountainous topography, between 700 and 1300 meters above sea level, this region is considered as unfavorable for the development of large-scale mechanized agriculture. Despite this, the region suffered a long history of deforestation and fragmentation (Joly et al. 2014), resulting in mosaic landscapes dominated by extensive pastures, Eucalyptus forestry and natural regrowth of secondary native forests (Tabarelli and Waldir 1999; Ronquim et al. 2016). The climate is tropical (Köppen System), with higher rainfall in summer (Morellato et al. 2000).

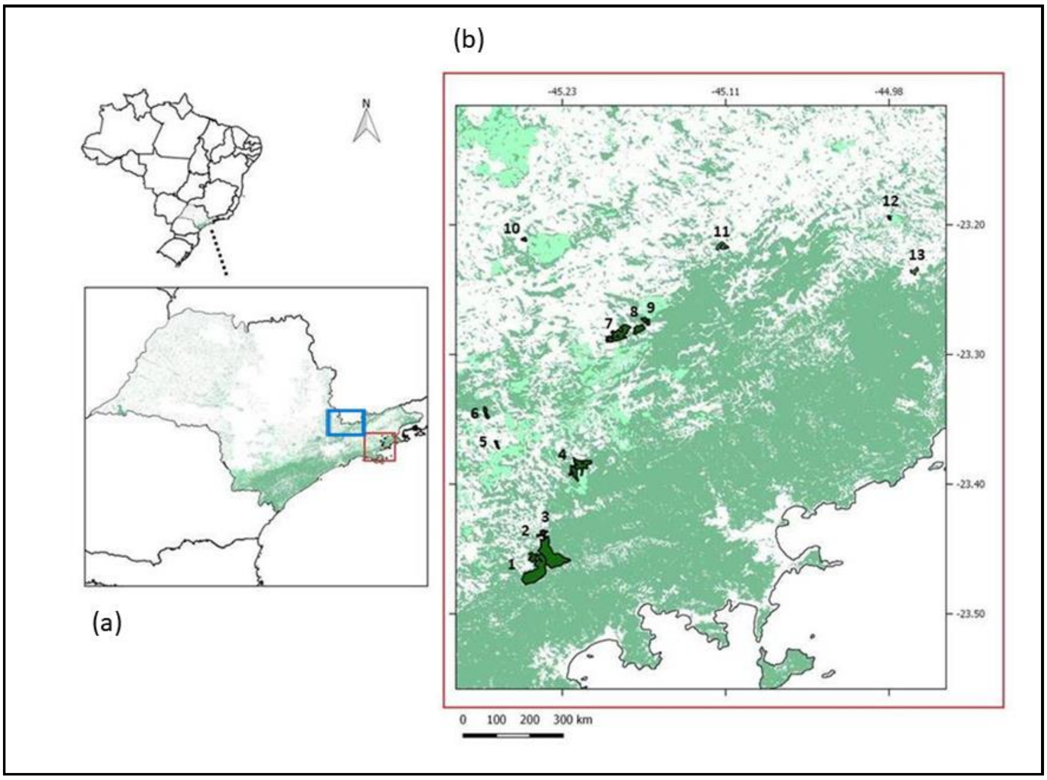

Figure 1. Study area. a) São Paulo State, the red square is the region where we performed the field-work and blue square is the region where Romitelli and D'Albertas collected the additional biomass data. b) Forest fragments where we made the estimates, spread over an area of 1184 square kilometers.

Field estimates of AGB

We randomly chose thirteen of the 59 fragments of secondary forest, contiguous to silviculture and pasture matrix. We identified and mapped the fragments by Google Earth images from the Open-Layer tool of open-source GIS software, QGIS2.18.9 (Development Team 2015). We made one plot into each fragment at ~30 meters from the forest edges to the interior to reduce the transition effect between forest and the contiguous land-use. Plot dimensions were 10 x 100 m, totalizing 0.1 ha- size frequently used for assessing tropical forest carbon stocks from biomass (Magnago et al. 2015). We split each plot into ten sub-plots (10 x 10 m each one) making possible a refined comparison of estimates within the plot. We measured the diameter at breast height (DBH) and the height of trees with DBH ≥ 3 cm. For DBH measurement we used measuring tape and the Leica DISTOtm A5 laser distance meter for tree height.

We calculated the AGB using tree DBH and height, with one allometric equation developed by Burger and Delliti (2008). We performed a comparison between the most used allometric equations for tropical forest biomass, to choose the most suitable for our study. For this purpose, we used the data of the 13 plots that we sampled and we calculated the AGB using four different equations for tropical forest (Scatena et al. 1993; Tiepolo et al. 2002; Chave et al. 2005; Moreira Burger et al. 2008). Figures S1 in the Supplementary Material, show that estimates using Tiepolo equation are very different than the estimates using the other three equations. Then, we decided to not include the Tiepolo equation in the next comparison. Unlike Chave, Burger and Delitti and Scatena equations included long diameter trees to formulate the equation, for that reason, Scantena and Burger and Delitti seem more suitable for Atlantic Forest remnants. As Sacatena equation is based on Puerto Rico forests, we consider that Burguer and Deliti is the most suitable equation for this study.

We calculated the total AGB at sub-plot and plot-level adding the AGB of all trees measured in the respective area, then, we transformed it in Megagrama per hectare (Mg ha^{-1}). We also calculated the confidence interval by bootstrapping.

To increase the field-based estimates of AGB, we included in the analyses an available data of AGB in Atlantic Forest fragments (Romitelli 2014; D'Albertas et al. 2018). D'Albertas and Romitelli performed the estimates of forest AGB in the neighbor mountain chain in the same forest range. They used a consistent methodology but different plot format and dimensions, hence, we included the differences in plot size and format in the analyses. Since the DBH and height of individual trees were available for each sampling point of the additional data set, we re-calculated the AGB using Burger and Delitti equation to standardize with the rest of the data. We also calculated the confidence interval by bootstrapping.

Pantropical aboveground biomass density map (PABDM)

We choose PABDM (Baccini et al. 2012) to perform the comparison because of its highest spatial resolution (30m) between the available biomass tropical maps. The spatial resolution of the PABDM made possible the comparisons with our plot size. We also tested the map of Englund et al (2017) with 50 m of spatial resolution -one more recent map for Brazil-, but we considered that the Englund map did not represent the variability in AGB at local scale (Figure S2).

We downloaded the PABDM of the studied region from the Global Forest Watch website (GWF) in tiff format (World Resources Institute 1997). The PABDM is a multisource map based LIDAR data, multispectral surface reflectance image from LANDSAT (at 30 m spatial resolution) and field data collected in the global tropics from 2008 to 2010. Baccini and collaborators also produced and made available an uncertainty map that considers the errors from allometric equations and the process.

Comparison of biomass values from field-work and PABDM

To compare the AGB estimates from field-work with the PABDM, we overlapped the map with the sampling points. We performed three comparison levels. (a) Sub-plot level; we compared the AGB of each 10 by 10 meters sub-plot made in the field-work, with the AGB values of pixels overlaid. When more than one sub-plot fell into a single pixel, we added the AGB from all the plots overlapping the pixel. (b) Plot level, comparing the total AGB from the plot with the average value of pixels covered by the plot (2- 4 pixels). (c) Buffer level, we create a buffer with the plot size as the radio size. In this case, we compared the mean pixel value within the buffer with the total AGB estimated at the whole plot. (d) Fragment level; we compared the average pixel value in the fragment boundaries with the AGB of each field plot. We performed the (a) and (b) comparison only when the initial and final points of the plot were available, on the contrary, we performed the (c) comparison. We also performed the (d) comparison, only when we know the fragment boundaries (Figure S3). We calculated all the pixel mean values using the Zonal Statistic tool of QGIS 2.18.9.

Variables that could explain the results of comparisons between PABDM and field estimates of AGB

We explored some variables that could influence the AGB values from the map or from the fieldwork. We chose hillshade, slope, and elevation because some studies pointed that these variables may influence RS products (Liu et al. 2008; Barbosa et al. 2014) and the forest AGB (Detto et al. 2013). Additionally, we calculated the forest cover around 500 m of the plot centroid, as a measure of resources available for forest maintaining and regrowth, because this variable also may influence the AGB (Romitelli 2014; Melito et al. 2017). We included in the model a differential weight for each AGB value, according to the errors of both estimates, then, the estimates with lower error had more importance in the model.

We calculated hillshade, slope and elevation for each sampling point, as the central value into the plot area or buffer with the plot size. We used the elevation digital model from topodata (INPE 2008) and the Digital Elevation Model tool from Qgis to obtain the values of these variables.

To calculate the forest cover around (500 m buffer) of each sampling point we used the Atlantic Forest map of Mapbiomas platform (Mapbiomas.org 2018), from 2015, because this year is the middle year of the range between 2013 and 2017, the period where both data sets were collected.

Finally, considering that the authors of the PABDM used the Chave equation for the AGB from fieldwork, we calculated the AGB also using the Chave equation with our data, in that way we explored the effect of using different equations.

Statistical analysis

We tested simple models with three response variables looking for any variable or combination of variables that could explain the results of the comparisons. The models we tested were: (a) Field biomass and PABDM as response variables in independent models. We applied this test to explore the variables that influence both AGB estimates independently, (b) corrected difference between field biomass and PABDM:

$$\left(\frac{Field\ biomass - PABDM\ biomass}{Field\ biomass}\right) \qquad \text{Equation 1}$$

We used the R environment (R Development Core Team 2017) to perform the analysis.

Results

Comparison of biomass values from fieldwork and PAGBDM

Estimates of AGB obtained from field-work and those obtained from the PABDM exhibited high variability and uncertainty. Figure 2 shows the comparison at pixel average by plot level, where the PABDM estimates of AGB were between 1.2 and 24 times higher than the estimates from fieldwork.

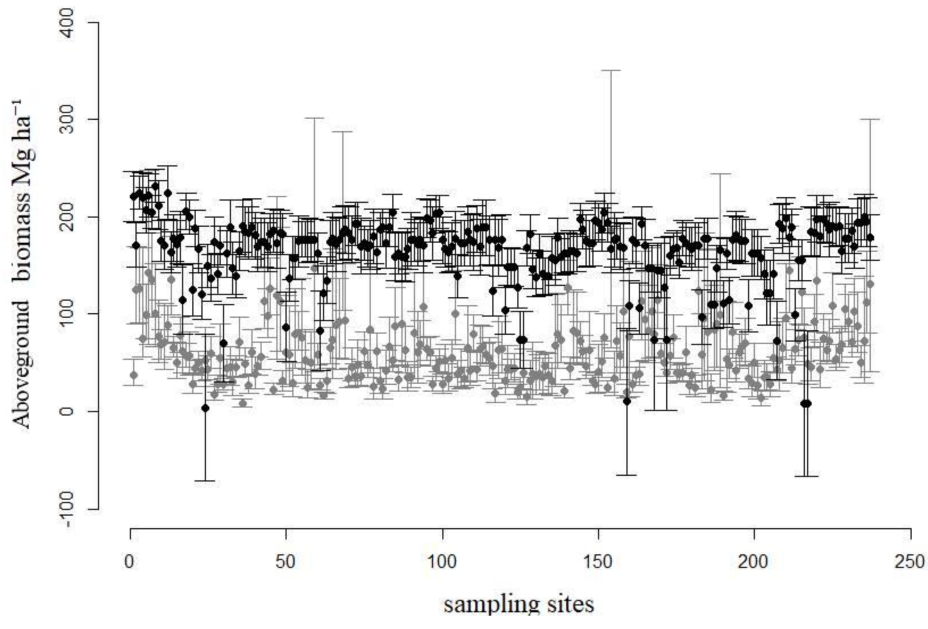

Figure 2. Estimates of AGB from field plots (gray dots) using Burger and Delitti allometric equation, compared with data from PABDM (black dots). Bars are the uncertainty and bootstrapping errors.

The PABDM values were higher than the field-based estimates also when the comparisons were performed at the fragment and also at the sub-plot level (Figure S2).Table S1 summarizes the AGB estimated from fieldwork in 245 sampled plots (~10 hectares of forest) and the 95% confidence interval associated. AGB was highly variable between plots, ranging from 7.97 Mg ha^{-1} to 185.66 Mg ha^{-1}.

Possible variables explaining differences found between PABDM and field estimates of biomass

We did not find a correlation between hillshade, slope, elevation and forest cover around 500 m (Spearman correlation < 0.5, Table S2). Thus, we could potentially use all of them as explanatory variables in the models. However, we did not identify any explanatory variable. Also, the model that has a corrected difference between field estimates and PABDM estimates as the response variable, was not significant (R^2 = -0.0110, p> 0.05). The model using both estimates as response variables in independent models were significant, but the explanation power of the variables was very weak. (R^2 = 0.0346, p<0.05). We found a reduction of 53% of the average difference between the AGB estimates from fieldwork, re-calculated using Chave equation, and the estimates from the PABDM (Figure S3).

Discussion

Our finding confirms that the PABDM should be revised to include local variability in secondary forest biomass, as Mitchard et al. (2014b) and Davila (2017) suggested for pantropical biomass maps. In the comparisons that we performed of AGB values from the PABDM and field-based estimates, the PABDM produced higher values of AGB than field estimates. Some reasons could explain these differences.

First, all the field estimates used to calibrate the PABDM in Brazil are located in the Amazon biome; it may cause reduced accuracy in other biomes (Englund et al. 2017). Disparities between Amazonian and Atlantic Forest characteristics can influence the AGB in both ecosystems. Relief is one of them, after all, is considered one of the major drivers of AGB heterogeneity (De Castilho et al. 2006). Analyses of RS resources are complex where relief is large compared to vegetation height (Harding and Carabajal 2005). In spite of recent advances to correct the error of AGB estimates in steep-slope areas using RS methods, errors remain high due to the difficulty of minimizing satellite data distortion in areas with heterogeneous topography (Liu et al. 2008). One reason that could explain the lack of influence of the three variables on AGB is that the spatial resolution of lightness, slope and elevation data can reduce the capacity to explain AGB at point scale. Local variation in topographic slope, for example, can better explain the aboveground forest carbon (Temesgen et al. 2015).

Another disparity between the Amazon and the Atlantic forests is the disturbance regime and history of human occupation (Fearnside 2005). Amazonian ecosystems experienced relatively recent fragmentation process and present a simplified spatial structure (Broadbent et al. 2008; Haddad et al. 2015). Thus, it does not represent the wide range of fragmented landscapes observed in tropical regions as Atlantic Forest (D'Albertas et al. 2018). Most of the sites where we sampled and those from the additional AGB data, are located in regions with high human disturbances.

Another reason that could explain the differences found in AGB estimates is the equation used to perform the field estimates of AGB in the PABDM. The authors used the equation proposed in Chave (2005) for tropical regions. This equation was developed based on a broad array of environmental conditions among the tropical forest of America, Asia and Oceania. In Brazil, they used data from the Amazon region (Chave et al. 2005). Estimate AGB for the Atlantic Forest using allometric equations based on more developed forests would lead to the overestimation of Atlantic Forest AGB (Vieira et al. 2008). According to that, re-calculating the field AGB using the Chave equation reduced in more than 50% of differences found between PABDM and field estimates. We highlight that Burger and Delliti equation is suitable for calculating Atlantic Forest biomass since, it was proposed based on the forests with the same characteristics of Atlantic Forest, contrary to Chave equation, that included mature forest as the Amazon forest in the calculations.

As reported by Englund and collaborators (2017), that performed a comparison between biomass maps for Brazil, the PABDM can be considered accurate for natural vegetation that is largely untouched and has high biomass content. Nonetheless, 80% of the data that we used to perform the comparisons are from protected areas that are supposed to be the most untouched among Atlantic Forest remnants.

The GFW platform, where PABDM is available, establishes that the map provides more accurate estimates when aggregated in areas around 5000 and 10000 hectares (World Resources Institute, 1997). In consequence, the PABDM is not a suitable resource for estimates of AGB in Atlantic Forest, since 83.4% of fragments in this biome are smaller than 50 ha, and 97% are smaller than 250 ha (Ribeiro et al. 2009).

Most of the fragments where we do the fieldwork are smaller than 250 ha, then estimates in those fragments may have reduced accuracy.

The GFW platform states that the accuracy of PABDM estimates is reduced when a single pixel is compared with small areas (World Resources Institute, 1997). In consequence, overestimates of AGB may occur and to lead inadequate support for decision-makers in calculate the reduction in greenhouse gas emissions or developing successful resource management policies (Davies et al. 2011; Englund et al. 2017). Reducing the uncertainty at the pixel level would require higher resolution data from RS instruments to capture the spatial variability of forest structure (Asner et al., 2010). We found that estimates from the PABDM are higher than field estimates at the sub-plot level.

It is important to consider that changes in AGB as a result of the degradation process are difficult to detect with RS because they do not imply changes in forest area (Houghton 2005). Moreover, positive impacts as enhancement of forest carbon stock from REDD+ activities on local or regional level may not be captured by RS (Asner et al. 2002; Shearman et al. 2009). Variation in our field estimates at the sub-plot level could be explained by case-specific human disturbances as selective logging, presence of pipelines or transmission lines and road creation, which are hard to be detected in the PABDM estimates.

Implications of using one or another method to estimate AGB targeted to planning and political strategies, as payment for ecosystem services, can be analyzed from an economic perspective, but also an ecological one. Considering the Carbon price by Mg ha^{-1}, a hypothetical private property with 50 ha of Atlantic Forest could be paid at less twice more using the PABDM than using field estimate. Applying a correction factor to reduce the estimation from the PABDM could be a good option.

Conclusions

This study revealed that the AGB estimates of Atlantic Forest fragments by PABDM are higher than field estimates. The allometric equation used is responsible for a big part of the differences found. Nonetheless, even if the same allometric equation were used to calculate AGB in the field, there is no relationship between AGB values from both approaches. Additionally, we consider that the calibration of the RS resources made using data from other biome is responsible for the differences found. We highlight that both kinds of estimates have big uncertainties and unknown accuracy. The choice to use one or the other one must be taken considering the objectives, the spatial extent and the affected social agent by the governmental project.

Acknowledgments

We thank Francisco D'albertas and Isabella Romitelli for providing the additional data set of AGB and the Profs. Drs. Paulo Inácio de K. L. de Prado, Vânia Regina Pivello Alexandre de Oliveira and Jomar Magalhães Barbosa for commenting on earlier versions of this manuscript.

The fieldwork of this study in 2017-2018 was mainly supported by National Geographic Society Committee for Research and Exploration (Grant #CP-080ER-17) and also by the Coordination for the Improvement of Higher Level -or Education-Personnel (CAPES-PROEX). C.Z.R was supported by PhD's fellowship from the Brazilian Ministry of Education (CAPES-DS, 2016–2019).

Supplementary Material

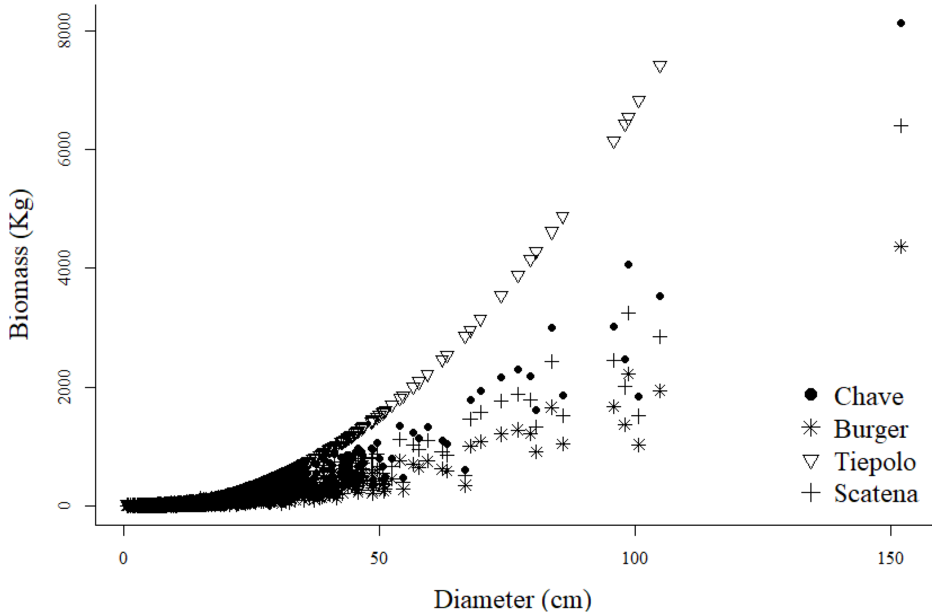

Figure S1 Comparison between allometric equations for tropical forests.

Source: Burger and Delitti, 2008; Chave et al., 2005; Scatena et al., 1993; Tiepolo et al., 2002**.**

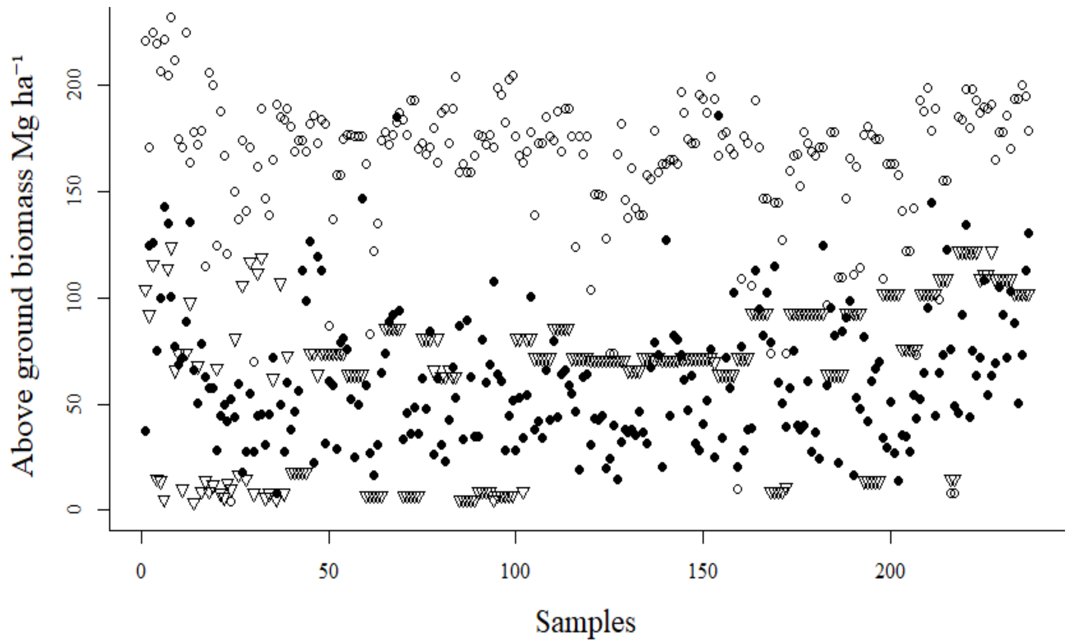

Figure S2 Comparison between PABDM, field estimates and Englund map. Fill dots are the AGB values from field work, open circles are AGB values from PABDM and triangles are AGB from Englund map.

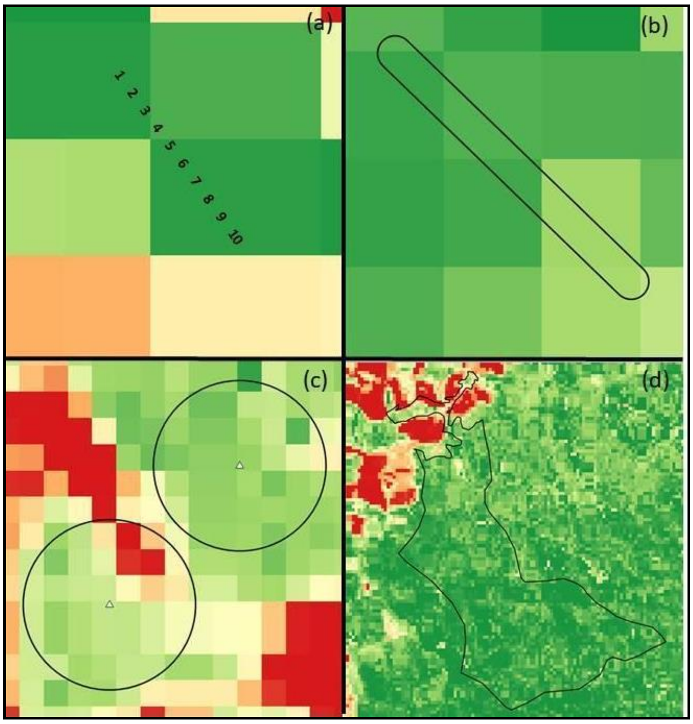

Figure S3 Comparison level (a) Sub-plot level, (b) Plot level, (c) Buffer level, (d), Fragment level

Table S1 Raw data of AGB from fieldwork 1: (D'Albertas et al., 2018), 2: (Romitelli, 2014b), 3: our field data.

Samplecode	AGB (Mg ha^{-1})	Confidence Interval		Data source	Plot size (ha)
		2.50%	97.50%		
1	69.04	58.81	80.06	2	0.1
2	51.45	34.22	71.29	2	0.1

Samplecode	**AGB (Mg ha^{-1})**	**Confidence Interval**		**Data source**	**Plot size (ha)**
		2.50%	**97.50%**		
3	78.76	60.82	98.1	2	0.1
4	63.95	38.32	90.01	2	0.1
5	59.03	45.92	72.52	2	0.1
6	61.4	41.15	86.81	2	0.1
7	29.84	20.48	40.01	2	0.1
8	45.51	38.46	53.21	2	0.1
9	51.46	41.04	63.39	2	0.1
10	42.39	31.85	55.03	2	0.1
11	53.93	27.24	89.03	2	0.1
12	43.88	32.54	56.51	2	0.1
13	60.88	46.61	78.98	2	0.1
14	18.25	12.86	27.05	2	0.1
15	29.93	21.57	39.59	2	0.1
16	56.95	30.9	94.78	2	0.1
17	28.38	22.89	34.83	2	0.1
18	45.68	37.47	55.59	2	0.1
19	45.18	28.46	67.39	2	0.1
20	30.8	16.37	55.11	2	0.1
21	48.39	39.16	58.86	2	0.1
22	71.83	50.8	96.12	2	0.1
23	8.33	4.83	13.41	2	0.1

Samplecode	AGB (Mg ha^{-1})	Confidence Interval		Data source	Plot size (ha)
		2.50%	**97.50%**		
24	49.78	36.43	65.29	2	0.1
26	29.98	21.28	40.1	2	0.1
27	65.18	42.71	91	2	0.1
28	37.49	26.4	53.65	3	0.1
29	124.71	91.59	168.06	3	0.1
30	125.58	85.02	168.72	3	0.1
31	75.19	55.23	98.6	3	0.1
32	99.8	75.7	133.24	3	0.1
33	142.63	65.65	255.51	3	0.1
34	135.23	96.48	188.1	3	0.1
35	100.6	69.76	153.41	3	0.1
36	77.4	48.49	112.98	3	0.1
37	68.64	54.2	85.03	3	0.1
38	71.8	41.87	112.46	3	0.1
39	88.96	70.42	110.29	3	0.1
40	136.02	96.48	178.96	3	0.1
41	38.27	23.29	55.6	1	0.03
42	46.77	36.96	56.52	1	0.03
43	56.2	42.7	69.38	1	0.03
44	113.18	84.68	146.41	1	0.03
45	98.63	74.57	125.08	1	0.03

Samplecode	AGB (Mg ha^{-1})	Confidence Interval		Data source	Plot size (ha)
		2.50%	**97.50%**		
46	126.42	98.95	160.08	1	0.03
47	22.63	16.91	28.74	1	0.03
48	119.44	53.1	222.44	1	0.03
49	112.96	59.08	187.08	1	0.03
50	31.24	20.57	43.16	1	0.03
51	60.76	27.5	114.25	1	0.03
52	58.74	25.16	113.22	1	0.03
53	28.98	15.41	51.41	1	0.03
54	79.24	46.25	127.38	1	0.03
55	81.05	62.63	104.16	1	0.03
56	75.76	36.49	130.91	1	0.03
57	52.47	29.62	83.21	1	0.03
59	24.96	13.76	43.78	1	0.03
60	49.83	22.98	81.82	1	0.03
61	146.69	40.72	299.12	1	0.03
62	58.58	47.35	70.12	1	0.03
63	27.25	21.74	33.39	1	0.03
64	16.42	12.83	20.27	1	0.03
65	31.15	18.49	47.82	1	0.03
66	64.89	49.04	86.63	1	0.03
67	74.16	33.94	141.69	1	0.03

Samplecode	AGB (Mg ha^{-1})	Confidence Interval		Data source	Plot size (ha)
		2.50%	**97.50%**		
68	89.15	43.93	158.9	1	0.03
69	91.99	53.7	139.93	1	0.03
70	185.06	99.74	293.04	1	0.03
71	93.96	55.06	152.02	1	0.03
72	33.34	24.44	42.66	1	0.03
73	45.83	31.52	64.75	1	0.03
74	36.08	25.38	48.56	1	0.03
75	48.29	26.77	76.63	1	0.03
76	36.29	25.19	51.44	1	0.03
77	62.24	44.92	81.89	1	0.03
78	48.1	34.66	62.26	1	0.03
79	84.4	40.07	150.63	1	0.03
80	26.07	13.34	46.53	1	0.03
81	62.33	44.16	82.02	1	0.03
82	31.11	19.61	44.67	1	0.03
83	23.01	12.69	34.06	1	0.03
84	42.51	28.09	64.22	1	0.03
85	67.15	44.7	96.2	1	0.03
86	52.72	40.61	66.86	1	0.03
87	87.18	54.94	130.01	1	0.03
88	33.23	20.97	45.86	1	0.03

Samplecode	AGB (Mg ha⁻¹)	Confidence Interval		Data source	Plot size (ha)
		2.50%	**97.50%**		
89	89.52	49.26	150.31	1	0.03
91	62.72	41.28	91.19	1	0.03
92	34.69	22.76	51.05	1	0.03
93	34.88	25.17	45.14	1	0.03
94	80.08	33.14	142.94	1	0.03
95	60.39	28.66	98.62	1	0.03
96	68.81	47.57	93.86	1	0.03
97	107.93	65.68	158.77	1	0.03
98	63.98	52.24	76.45	1	0.03
99	61.05	46.86	77.43	1	0.03
100	28.36	21.47	37.2	1	0.03
101	44.3	33.08	58.18	1	0.03
102	51.49	41.66	63.74	1	0.03
103	28.18	18.26	38.93	1	0.03
104	53.1	39.77	68.63	1	0.03
105	33.94	20.87	49.51	1	0.03
106	54.48	36.13	74.76	1	0.03
107	100.32	70.24	141.57	1	0.03
108	38.27	26.92	51.73	1	0.03
109	41.91	24.22	65.66	1	0.03
110	34.37	24.07	44.58	1	0.03

Samplecode	AGB (Mg ha^{-1})	Confidence Interval		Data source	Plot size (ha)
		2.50%	**97.50%**		
111	65.92	30.75	107.98	1	0.03
112	42.56	25.55	62.28	1	0.03
113	79.87	62.5	100.18	1	0.03
114	43.7	31.11	59.3	1	0.03
115	64.22	46.48	86.68	1	0.03
116	66.19	51.16	85.5	1	0.03
117	58.93	48.12	70.4	1	0.03
118	55.29	36.11	76.54	1	0.03
119	46.24	25.24	71.45	1	0.03
120	19.19	9.67	29.66	1	0.03
121	62.75	34.44	97.21	1	0.03
123	64.23	39.11	92.64	1	0.03
124	31	17.54	47.96	1	0.03
125	43.07	24.92	67.85	1	0.03
126	42.84	32.77	54.2	1	0.03
127	44.43	31.27	59.06	1	0.03
128	19.57	12.86	27.44	1	0.03
129	24.2	14.45	35.73	1	0.03
130	39.94	23.72	65.83	1	0.03
131	14.69	8.12	22.36	1	0.03
132	32.1	17.6	54.23	1	0.03

Samplecode	AGB (Mg ha^{-1})	Confidence Interval		Data source	Plot size (ha)
		2.50%	**97.50%**		
133	38.37	12.32	70.18	1	0.03
134	36.54	17.47	63.33	1	0.03
135	38.2	22.69	58.84	1	0.03
136	35.13	15.95	56.75	1	0.03
137	46.38	33.07	59.42	1	0.03
138	37.07	19.67	58.29	1	0.03
139	31.4	15.78	49.39	1	0.03
140	67.28	26.94	118.67	1	0.03
141	79.22	44.69	121.06	1	0.03
142	73.46	49.13	106.85	1	0.03
143	20.69	13.58	28.85	1	0.03
144	126.93	99.68	157.87	1	0.03
145	44.27	33.6	57.58	1	0.03
146	82.62	49.74	122.79	1	0.03
147	80.62	50.58	118.88	1	0.03
148	72.96	54.9	93.54	1	0.03
149	61.44	47.25	80.09	1	0.03
150	46.94	33.68	65.04	1	0.03
151	63.45	41.23	97.98	1	0.03
152	31.56	26.49	37.47	1	0.03
153	28.24	18.28	39.52	1	0.03

Samplecode	AGB (Mg ha-1)	Confidence Interval		Data source	Plot size (ha)
		2.50%	**97.50%**		
155	40.7	20.02	66.37	1	0.03
156	51.86	34.8	73.84	1	0.03
157	76.02	55.37	101.57	1	0.03
158	24.93	19.46	31.03	1	0.03
159	185.57	63.07	345.91	1	0.03
160	33.95	15.89	60.93	1	0.03
161	72.14	38.14	108.99	1	0.03
162	57.4	34.84	89.53	1	0.03
163	102.67	49.1	178.21	1	0.03
164	20.2	14.6	27.78	1	0.03
165	77.33	14.84	154.19	1	0.03
166	28.19	19.67	41.22	1	0.03
167	23.69	17.86	30.75	1	0.03
168	37.98	31.69	45.92	1	0.03
169	38.55	28.06	50.45	1	0.03
170	113.1	75.91	159.58	1	0.03
171	94.69	54.12	145.53	1	0.03
172	82.51	50.33	128.84	1	0.03
173	102.79	55.93	172.75	1	0.03
174	79.08	59.65	100.26	1	0.03
175	115.05	84.8	150.58	1	0.03

Samplecode	AGB (Mg ha^{-1})	Confidence Interval		Data source	Plot size (ha)
		2.50%	**97.50%**		
176	60.03	50.22	69.87	1	0.03
177	50.25	36.05	68.38	1	0.03
178	39.65	30.52	50.29	1	0.03
179	57.57	43.48	74.88	1	0.03
180	75.47	55.7	100.98	1	0.03
181	40.33	30.87	49.95	1	0.03
182	38.34	29.17	47.62	1	0.03
183	40.16	31.3	49.63	1	0.03
184	60.82	36.82	86.15	1	0.03
185	27.37	16.99	40.31	1	0.03
187	37	30.26	43.85	1	0.03
188	24.13	15.32	35.1	1	0.03
189	124.34	88.63	172.57	1	0.03
190	58.78	22.71	98.18	1	0.03
191	95.3	31.62	182.07	1	0.03
192	82.23	17.71	169.51	1	0.03
193	22.63	9.83	39.76	1	0.03
194	84.04	43.11	131.09	1	0.03
195	90.55	44.3	159.58	1	0.03
196	98.9	24.1	242.52	1	0.03
197	16.43	11.51	22.07	1	0.03

Samplecode	AGB (Mg ha^{-1})	Confidence Interval		Data source	Plot size (ha)
		2.50%	**97.50%**		
198	53.2	20.03	108.44	1	0.03
199	47.82	33.71	63.6	1	0.03
200	81.54	53.38	113.09	1	0.03
201	41.86	29.34	58.65	1	0.03
202	61.13	46.03	80.74	1	0.03
203	66.82	51.59	83.91	1	0.03
204	70.05	46.97	98.77	1	0.03
205	34.12	23	47.35	1	0.03
206	29.63	15.49	45.94	1	0.03
207	50.85	35.14	70.64	1	0.03
208	26.7	12.63	46.93	1	0.03
209	13.9	6.81	22.22	1	0.03
210	35.22	20.43	53.02	1	0.03
211	34.89	22.13	48.53	1	0.03
212	27.66	16.25	41.62	1	0.03
213	54.49	40.31	71.29	1	0.03
214	43.25	30.94	57.09	1	0.03
215	52.48	20.69	96.89	1	0.03
216	64.97	38.69	95.64	1	0.03
217	95.46	51.2	150.43	1	0.03
218	144.5	103.93	191.21	1	0.03

Samplecode	AGB (Mg ha-1)	Confidence Interval		Data source	Plot size (ha)
		2.50%	**97.50%**		
220	44.83	29.4	65.46	1	0.03
221	64.56	49.6	81.36	1	0.03
222	73.33	57.09	89.19	1	0.03
223	122.49	88.02	157.2	1	0.03
224	75.86	52.23	106.94	1	0.03
225	49.39	28.01	74.49	1	0.03
226	46	31.02	65.59	1	0.03
227	92.02	67.29	123.1	1	0.03
228	134.35	80.66	194.55	1	0.03
229	43.76	24.39	70.52	1	0.03
230	75.17	53.08	98.47	1	0.03
231	63.53	47.57	80.74	1	0.03
232	71.95	52.47	93.33	1	0.03
233	108.25	79.38	141.39	1	0.03
234	54.32	42.65	68.12	1	0.03
235	63.68	46.46	84.19	1	0.03
236	69.31	51.42	88.46	1	0.03
237	105.24	83.59	129.79	1	0.03
238	91.94	66.64	120.58	1	0.03
239	71.87	56.91	88.48	1	0.03
240	103.42	74.97	138.04	1	0.03

Samplecode	AGB (Mg ha-1)	Confidence Interval		Data source	Plot size (ha)
		2.50%	**97.50%**		
241	88.05	60.82	122.25	1	0.03
242	50.19	35.5	69	1	0.03
243	72.95	31.1	131.9	1	0.03
244	112.69	79.22	161.8	1	0.03
245	130.65	39.91	293.53	1	0.03

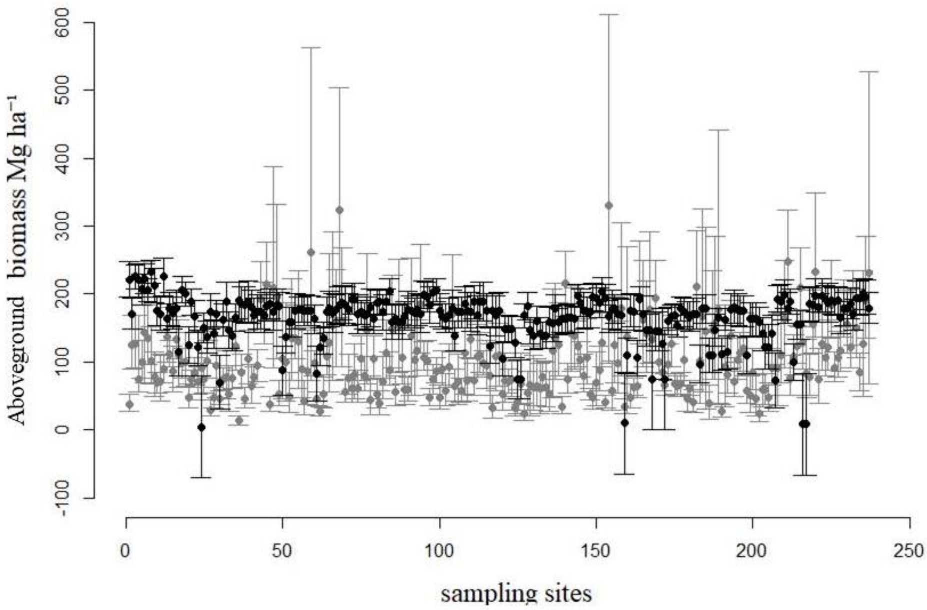

Figure S3 AGB estimated from field plots (gray dots) using Chave allometric equation, compared with data from PABDM (black dots). Bars are uncertainty and bootstrapping error.

Table S2 Correlation test between explanatory variables

Variables		Correlation
Lightness	Elevation	0.12
	Slope	-0.18
	Forest cover	-0.32
Elevation	Slope	0.09
	Forest cover	0.34
Slope	Forest cover	-0.02

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Chapter 2

Carbon stock in landscapes covered by a gradient between

Atlantic forest fragments and Eucalyptus silviculture

Catalina Zuluaga Rodríguez, Susana López Caracena, Rozely Ferreira dos Santos

Abstract

Land-use and land-cover changes intended to meet society's demands resulted in landscapes with different elements, which provide a range of ecosystem services. In these heterogeneous landscapes, the conservation of the forest remnants has a critical role in the carbon flux since changes in the forest cover can influence the atmospheric CO_2 concentrations. How to identify the appropriate relationship between the forest carbon services and the expected benefits of the land-uses by social agents is a question to be answered. Contributing to this issue, we analyzed how the forest cover reduction and the expansion of silviculture affect the carbon stock at the catchment scale in a Brazilian Atlantic Forest region. We studied fourteen catchments with natural forest and Eucalyptus plantations in a gradient from 10% to 100% of natural forest cover. We estimated the natural forest biomass with fieldwork and carried out a bibliographic survey of the carbon stock in different ages of Eucalyptus plantations in Brazil. The results show low carbon stocks in the natural forest and high carbon stocks in silviculture. We argue that historical human interference in the forest added to the producers' decision to cut Eucalyptus trees were the basic conditions for this outcome.

Keywords: carbon ecossystem services, climate regulation, biomass, tropical forest, silviculture

Resumo

As mudanças na cobertura e no uso da terra, destinadas a satisfazer às demandas da sociedade resultaram em paisagens com vários elementos, os quais oferecem uma gama de serviços ecossistêmicos. Nestas paisagens heterogêneas, a conservação dos remanescentes florestais tem um papel crítico nos fluxos de carbono, uma vez que as mudanças na cobertura florestal podem influenciar as concentrações atmosféricas de CO_2. Como identificar a relação apropriada entre os serviços de carbono da floresta e os benefícios esperados pelos agentes sociais em virtude de um uso da terra ainda é uma questão a ser respondida. Focados nesse debate, analisamos como a redução na cobertura florestal natural e a expansão da silvicultura afetam o estoque de carbono em escala de bacia hidrográfica em uma região da Mata Atlântica. Estudamos quatorze microbacias com florestas naturais e plantações de eucalipto em um gradiente de 10% a 100% de floresta natural. Estimamos a biomassa das florestas no campo e realizamos um levantamento bibliográfico do estoque de carbono em plantações de eucalipto de diferentes idades no Brasil. Os dados mostraram baixos estoques de carbono na floresta natural e altos estoques de carbono na silvicultura. Argumentamos que a interferência histórica do homem sobre a floresta, adicionada à decisão dos produtores sobre o corte do eucalipto, foram as condições básicas que justificam esse resultado.

Palavras-chave: Serviço ecossistêmico, regulação climática, biomassa, florestas tropicais, silvicultura.

Introduction

Several natural ecosystems have been highly transformed with the aim to meet demands for food, fiber, water, and shelter (Foley et al. 2005; Le Quéré et al. 2016). The world's forests total area decreased 3% between 1990 and 2015 (Keenan et al. 2015). According to Curtis (2018), 27% forests loss can be attributed to deforestation through permanent land-use change for commodity markets (i.e., cattle meat, soy, palm oil, and wood fiber).

Forest loss threats biodiversity (Betts et al. 2017) and biodiversity-mediated ecosystem services (ES) (Onaindia et al. 2013; Brockerhoff et al. 2017; Mori et al. 2017) like climate regulation. Forest growth is the result of carbon accumulation coming from the atmosphere and the benefit that humans get from this process is interpreted as global climate regulation ES (CICES v5.1) (Haines-young and Potschin 2018). The permanent deforestation process negatively influences the carbon sequestration and the capacity of the forests to act as carbon sinks (Baccini et al. 2017). Despite academic efforts to prove the importance of forest maintenance for climate regulation, the reduction of forests area continue in many countries (Keith et al. 2019; Quijas et al. 2019; Mateo-Vega et al. 2019; Funk et al. 2019)

In Brazil, the Atlantic forest is one of the 35 global hotspots of biodiversity (Ribeiro et al. 2011), but is the among most vulnerable forests of the country. The intense process of deforestation and fragmentation since the European colonization is responsible for its degradation (Ribeiro et al. 2011; Brazilian Institute of Geography and Statistics -IBGE 2017). Recent estimates indicate that the remaining area is between 16.3% and 28% of the original coverage of this biome (SOS Atlantic Forest

Foundation 2018; Rezende et al. 2018). Most of the forest remnants are fragments of intermediate forests constituted mainly by edge areas located on steep and high lands surrounded by an anthropogenic matrix (Tabarelli et al. 2012). In fact, Pavani et al (2018) predicted 3.7 million hectares of carbon stock loss in the Atlantic forest region until 2030.

Heterogeneous landscapes occupied by Atlantic forest remnants, grasslands, silviculture, and urban areas are intended to meet different human demands and must be managed for multifunctional purposes (Fantini et al. 2019). Planted forests for commercial purposes are one of the central components in this mosaic of land-uses. Brazil has 7.83 million hectares of planted forests intended for wood, pulp, paper, and energy production (Brazilian Institute of Trees-IBA 2019). The state of São Paulo has 17% of the forest plantations in Brazil, mostly taken by Eucalyptus species with fast growth, highly productive and short periods of harvesting (Brazilian Institute of Trees-IBA 2019). Planted forests are responsible for 91% of the total Brazilian wood produced for industrial proposes (Brazilian Institute of Trees-IBA 2019). In addition, they play an important role regarding environmental services, such as soil protection, carbon stock among others (Brockerhoff et al. 2013; Ferraz et al. 2013).

In Brazil, forest plantations were mainly established on degraded lands previously used as pasture and agriculture (Silva et al. 2016). In conjunction with the urban development were the main causes of deforestation (Tilman et al. 2011; Achard et al. 2014; FAO 2016). Several landscapes consist of various combinations of forest remnants and silvicultural stands, each of them contributing with a specific amount of carbon flux. How to identify the best relationship between ecosystem services that ensure the maintenance of ecological processes, and benefits social agents is a question to be answered by policymakers (Farley 2012; Albert et al. 2016). It is important to equalize both forest cover and silviculture in a way that keeps a good contribution of carbon stock at a landscape scale.

The aim of this paper is to analyze how the reduction of natural forest cover and the expansion of Eucalyptus silviculture affect the carbon stock at a catchment scale. Firstly, we calculated the carbon stock in initial and intermediate-advanced forests and in different ages of Eucalyptus silviculture. Then, we evaluated the carbon stocks at a catchment scale within different percentage combinations of forest cover and silviculture.

Methods

Study area

We studied fourteen catchments of second and third-order in the Brazilian Atlantic Forest located in the Paraiba Valley region of the Sao Paulo state, Brazil (Figure 1). We choose this region because of its national environmental and economic importance and because of the continued and intense process of land-use-change that resulted in high degradation of natural resources (Marengo and Alves 2005; Castilho et al. 2015; Hackbart et al. 2017). The region has an average annual temperature between 16 and 23ºC and an average annual rainfall of 1,400 mm^3 (Nunes and Calbete 2000). Natural forests in this region are classified predominantly as Montane Ombrophilous Dense Forest (Brazilian Institute of Geography and Statistics - IBGE 2012). The topography is steep and mountainous (700-1300 m.a.s.l.) and consequently, it is considered unfavorable for the development of large-scale mechanized agriculture. The region suffered a long history of deforestation and fragmentation (Joly et al. 2014) resulting in mosaic landscapes dominated by pastures, extensive Eucalyptus silviculture and natural regrowth of secondary natural forests (Ronquim et al. 2016).

We selected catchment as the unit of analyses because it is the smallest geomorphological unit that reflects the impacts of human activities (Leyton 2008). Additionally, catchments are often used in the development of management projects (Kaval 2019).

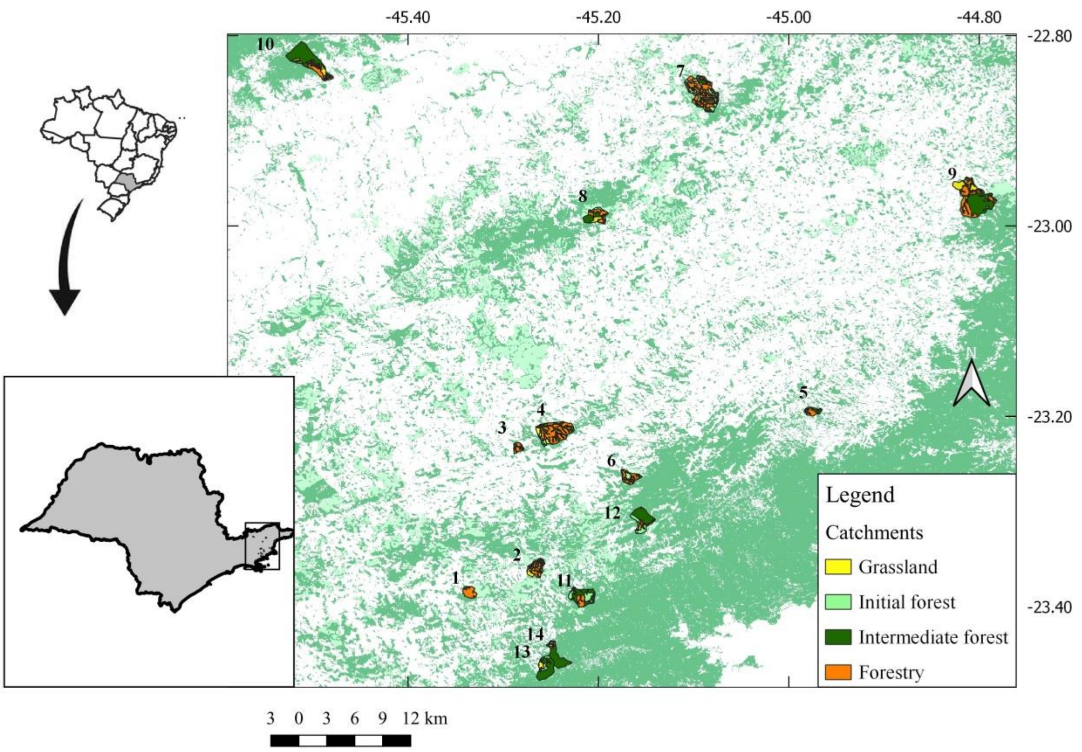


Figure 1. Study area in São Paulo State with the fourteen catchments.

Mapping land-use/cover and sampling sites selection

We mapped the land-use/cover of the Paraiba Valley region using visual interpretation of the satellite SPOT 5 of 2017 (spatial resolution 1:3,000 and Datum SIRGAS 2000), in QGIS2.18.9 (Development Team 2015). We selected fourteen catchments previously delimited by Hackbart (2017) with natural forest and Eucalyptus silviculture in a gradient between 10% to 100% of natural forest cover (Supplementary Material, Table S1). We also estimated the age of Eucalyptus silviculture stands using the *Historical Imagery* tool of Google Earth.

Field estimates

We randomly selected 23 fragments within the fourteen catchments using the *Random* tool of Excel software: twelve fragments in the intermediate-advanced stage and 11 in the initial stage. We determined the development stage of the fragments by visual interpretation. Advanced forest in the region is constrained to the National Park and we only sampled two fragments there.

During the fieldwork, we identified the selected fragments and checked the successional stage of the forest according to the land-use map previously made. Then, we used the GPS Garmin GPSMAP ® 78s to record the coordinates of the plot in each fragment.

We made one plot into each fragment at ~30 meters from the fragment edges to avoid wider effects of the transitioning area between forest and the adjacent land-use. The plots had 10 x 100 m, totalizing 0.1 ha. This size is frequently used for assessing tropical forest carbon stocks from biomass (Magnago et al. 2015). We measured diameters at breast height (DBH) using a measuring tape and the heights of trees with DBH ≥ 3 cm using a Leica DISTOtm A5 laser distance meter. We considered bifurcated or multiple stems as only one individual for DBH measures. We performed all the fieldwork between June 2017 and May 2018.

Biomass estimates

We used the allometric equation developed by Burger & Delitti (2008) using DBH and the height of each tree to estimate the individual aboveground biomass (Supplementary Material, Equation S1). We assessed four equations for aboveground biomass in tropical forest and concluded that Burger and Delitti equation is the most suitable for our data considering that the authors developed it using forest fragments located in a region close to our study region and with similar characteristics (See Ch.1, Figure S1). We calculated the biomass of the fourteen fragments by adding the values of all the trees in each sampled plot. The data was transformed in Megagram per hectare (Mg ha^{-1}).

Forest contribution to carbon stock

We calculated the carbon stock of natural forest using the aboveground biomass estimates from fieldwork and considering the carbon content as the 50% of dry biomass (IPCC 2006). We used the carbon stock from the fragments in the initial and intermediate-advanced forest to calculate the average carbon stock for each forest stage (Equations 1 and 2).

$$\overline{Ca} = \frac{\sum_{x=1}^{n_a} c_{a,x}}{n_a} \qquad \text{Equation 1}$$

Where $\overline{Ca}$ is the average carbon stock in the initial forest (Mg ha^{-1}), $C_{a,x}$ is the carbon stock in the sampled fragment *x* of the initial forest, n_a is the total sampled fragments in the initial forest (eleven in this case).

$$\overline{Cb} = \frac{\sum_{y=1}^{n_b} C_{b,y}}{n_b} \qquad \text{Equation 2}$$

Where $\overline{Cb}$ is the average carbon stock in the intermediate-advanced forest (Mg ha^{-1}), $C_{b,y}$ is the carbon stock in the sampled fragment *y* of the intermediate-advanced forest, n_b is the total sampled fragments in intermediate-advanced stage (twelve in this case).

We used the t-test to evaluate if initial and intermediate-advanced forests have different values of carbon stock. Then, we used the average carbon stock in initial and intermediate-advanced forest and the area covered with each successional stage to calculate the total contribution of each forest stage for each catchment (Equation 3). We also weighted the total carbon stock by the area of the catchment. The total contribution of the forest to the carbon stock in each catchment was the sum of the contributions of the initial and intermediate forest.

$$C_{f,z} = \frac{\left(\sum_{x=1}^{n_{a,z}} C_{a,x} \cdot A_{a,x}\right) + \left(\sum_{y=1}^{n_{b,z}} C_{b,y} \cdot A_{b,y}\right)}{A_{t,z}} \qquad \text{Equation 3}$$

Where $C_{f,z}$ is the total contribution of natural forest for carbon stock in each catchment *z* (Mg ha^{-1}), $C_{a,x}$ is the carbon stock of *x* forest fragment in stage *a*, in the catchment *z* (Mg ha^{-1}), $C_{b,y}$ is the carbon stock of *y* forest fragment in stage *b*, in the catchment *z* (Mg ha^{-1}), $A_{a,x}$ is the area of forest fragment *x* in the stage *a*, in the catchment *z* (ha), $A_{b,y}$ is the area of the fragment *y* in stage *b*, in the catchment *z* (ha), $A_{t,z}$ is the area of the catchment z (ha), $n_{a,z}$ is the number of fragments in the a stage, in the catchment z and $n_{b,z}$ is the number of fragments in the b stage, in the catchment z.

Silviculture contribution to carbon stock

We performed a literature review for Brazilian Eucalyptus silviculture stands and grouped by age classes (Table S2). Then, we tested for differences between classes using the Mann-Whitney test and used the classes that presented significant differences in carbon stock for the forward calculations, i.e. 1-2, 3-6, >6 yrs.

We calculated the contribution of silviculture to carbon stock at a catchment scale considering the age (years) and area (hectares) of the Eucalyptus stands, and the average carbon stock by classes (Equation 4).

$$C_{sz} = \left(\frac{\sum_{x=1}^{n}(A_{xz} \times \overline{C_{xz}})}{A_{tz}}\right) \qquad \text{Equation 4}$$

Where C_{sz} is the total carbon stock contribution of Eucalyptus stands of all ages in each one of the z catchments (Mg ha^{-1}), A_{xz} is the area of Eucalyptus stands of x age class in each one of the fourteen catchments, $\overline{C_{xz}}$ is the average carbon stock in Eucalyptus stands of x age class obtained from the literature and A_{tz} is the total area of each one of the z catchments (ha).

The total carbon stock in each of the fourteen catchments was calculated summing the carbon stock in the forest and in Eucalyptus stands (Equation 5).

$$C_{sj} = C_{fz} + C_{sz} \qquad \text{Equation 5}$$

Where C_{fz} is the total contribution of the forest for carbon stock in each one of the j catchments (Equation 4) and C_{sz} is the total carbon stock contribution of all ages Eucalyptus stands in each j catchment.

Results

We measured eleven fragments of initial forest (5,695 trees in 1.1 hectares) and twelve fragments of intermediate-advanced forest (7,373 trees, 1.2 ha). The percentage of dead trees in both the initial and intermediate-advanced forests was similar (4.6% and 4.7%, respectively). Catchments with more percentage of forest cover also have more intermediate-advanced forest fragments. There is no relationship between the initial forest area and the percentage of forest cover in the catchments.

Contribution of forest and silviculture to carbon stock

Table 1 shows the average carbon stocks in forest fragments in initial and intermediate-advanced stages and 3 age classes of Eucalyptus silviculture. The contribution of the forest to carbon stock was highly variable across the plots in both successional stages, varying from 3.88 to 26.09 Mg C ha^{-1} in initial forests and from 13.40 to 55.1 in intermediate-advanced forests. Results indicate a significant difference between the carbon stock in the initial forest and intermediate-advanced forest,($t = 4.00$, $p < 0.05$). For Eucalyptus silviculture the median values were significantly different, between 1-2 and 3-6 years: $w=7$, $p< 0.05$ and 3-6 and >6 years: $w=25$, $p<0.05$.

Table 1. Carbon stock in natural forest and Eucalyptus plantations

(Average and standard deviation)

Successional stage of forest/ age	**Carbon stock by area (Mg ha^{-1})**
Initial forest	16.89 ± 6.60
Intermediate-advanced forest	34.80 ± 12.07
Eucalyptus 1-2 yrs	9.65 ± 6.52
Eucalyptus 3-6 yrs	52.94 ± 21.54
Eucalyptus> 7 yrs	93.84 ± 12.89

Source: Forest data from field estimates and Eucalyptus data from the literature review presented in Supplementary Material (Table S2)

Figure 2 shows the descriptive statistics of the two groups of natural forests and the three age classes of Eucalyptus. We found atypical values of carbon stock in Eucalyptus according to the Z-score, and were removed. We used the average by groups for the subsequent analyses.

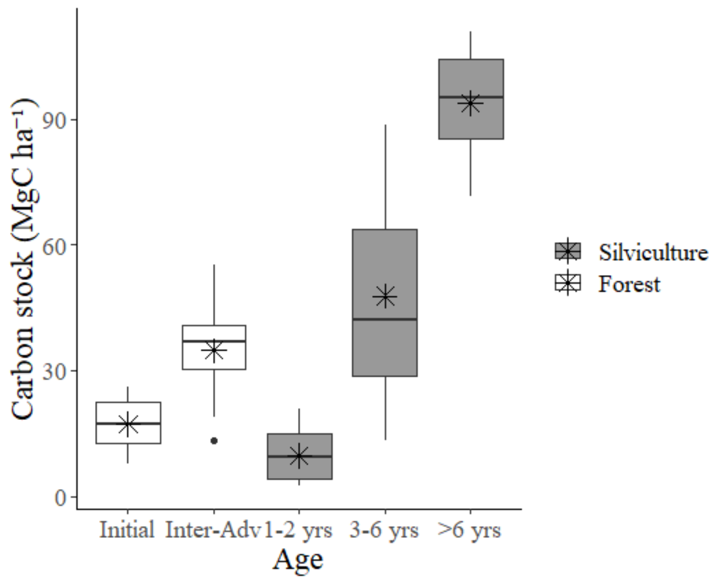


Figure 2. Carbon stock in initial and intermediate-advanced forest fragments and Eucalyptus forestry of 5 age ranges). Middle bars represent median values, boxes are first and third quartiles, and whiskers are the 95% confidence intervals.

Figure 3 shows carbon stocks in the catchments along the gradient of natural forest cover. The contribution of silviculture to carbon stock is significantly higher than the contribution of the natural forest. The initial forest has a lower contribution to carbon stock in all the catchments independently of the forest cover percentage. The forest contribution to carbon stock comes mainly from the intermediate-advanced stage, exceeding silviculture values when more than 70% of the region is covered by natural forest.

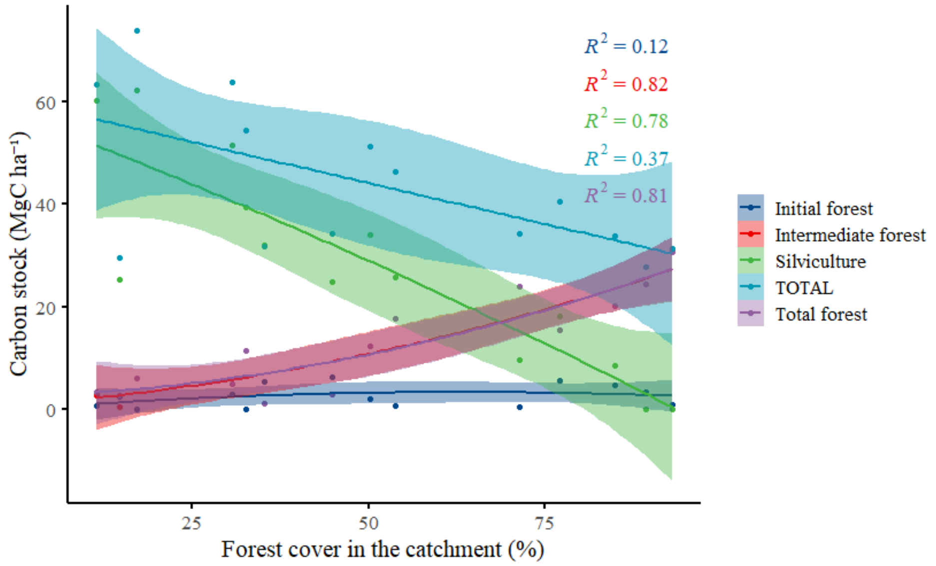


Figure 3. Carbon stock tendencies in the natural forests (initial and intermediate-advanced stages), silviculture and TOTAL (silviculture + natural forests) along the natural forest cover gradient in the catchments.

In the catchment scale, silviculture compensates the carbon stock in natural forests. Nonetheless, most of the Eucalyptus stands analyzed are above 5-7 years. Thus, they are above the typical harvesting age for paper production in Brazil. Table S2 (Supplementary Material) shows the percentage of Eucalyptus stands by age found in the fourteen catchments. Naturally, the unusual age of Eucalyptus stands strongly influenced the results of total carbon stock estimates.

Discussion

Carbon stock in initial and intermediate-advanced forests was lower than the majority of the values reported in the literature (Groeneveld et al. 2009; Ditt et al. 2010; Diniz et al. 2015; D'Albertas et al. 2018; Pyles et al. 2018). Pyles et al (2018) and Ditt et al (2010) found carbon stock estimates 48% and 76% higher than our data in the Atlantic forest in initial stage. Groeneveld et al (2009) and Ditt (2010) presented carbon stock estimates 50% and 69% higher than our estimates in intermediate-advanced forests. Yet, more recent evidence reports 41.27 ± 23.00 Mg C ha^{-1} in the intermediate-advanced stage of Atlantic forest fragments (D'albertas et al. 2018) and 15-52 Mg C ha^{-1} in the initial and intermediate-advanced forests (Diniz et al. 2015). These are similar results to ours but it is important to notice that previous studies used different allometric equations that may be overestimating or underestimating their results (Colmanetti et al. 2018; López and Ferreira 2019).

There are several possible explanations for the low carbon stock found in the natural forest. Putz (2011) pointed out the fragment area as influencing the carbon stock in the forest. According to the author, forest fragments smaller than 25 ha exhibit around 60% less carbon stock than bigger fragments as a consequence of the tree mortality. The median size of the fragments sampled in this study was 18 ha, most of them being smaller than 50 ha. Smaller fragments are more vulnerable to the influence of edge effects, which causes the replacement of mature trees by pioneer species with lower carbon stock (Stephenson et al. 2014; Haddad et al. 2015). Also, it causes structural homogenization between the edge and the core of the fragment (D'Albertas et al. 2018).

Some structural traits of the forest could indicate underlying processes. For example, we found small average DBH that in conjunction with the low carbon stock could be associated with ecological stagnation or even regression (Chazdon et al. 2016; López and Ferreira 2019).

High quantities of carbon stock in silviculture at a catchment scale are most likely because of the age of most of Eucalyptus stands. The rotation cycle of Eucalyptus for paper production in Brazil is between 5 and 6 years old (Almeida et al. 2007; Brazilian Institute of Trees-IBA 2019). Nonetheless, more than 80% of Eucalyptus stands in the study are over this age. We established personal communication with Suzano company (the main silviculture company in the region), but they did not provide explanations about this atypical behavior. If we assume that all Eucalyptus stands are industry-oriented, we can propose some hypotheses on this unexpected finding. First, the reduction in the international trade of paper because of China's economic slowdown is reducing paper production in Brazil (Valor 2019). Second more distant Eucalyptus stands could be maintained due to the comparatively high cost of transportation (Rönnqvist et al. 2003). Further interdisciplinary research and stronger synergy academy-industry are required to better understand this phenomenon.

In any case, Keith (2009) pointed to the high potential of Eucalyptus forest to stock carbon in its natural distribution area. Biological characteristics of Eucalyptus species and centuries of research led these species to expand throughout much of the world (Bennett 2010). In Brazil, Eucalyptus silviculture met particularly favorable edaphoclimatic conditions for its development (Colodette et al. 2014). Moreover, decades of continuous research have improved management practices (as site preparation, fertilization, vertical productivity, pests control) and genetic improvement, making Brazilian plantations the most productive in the world (Brazilian Institute of Trees-IBA 2019). Those reasons may explain the high carbon stock in Eucalyptus in our study areas and in other regions of Brazil.

As a result of that huge contribution of Eucalyptus silviculture to the carbon stock, catchments with less natural forest cover and more silviculture showed higher total carbon stock than catchments with larger natural forest cover. However, the situation of the catchments of this study should not be extrapolated for other areas of the country. occurs in other areas of the country, nor in the same region because the productive destination of Eucalyptus silviculture in Brazil does not match with silviculture stands overpassing the rotation cycle.

In order to recognize the carbon fluxes and other environmental aspects associated with the paper, it is important to consider each stage of the paper lifecycle, which ranges from the design and manufacturing stages to the end-of-life stage, and includes, recycling and disposal. Considering the results of this study we can suggest that management decisions must be focused on the enrichment of natural forest remnants to increase their capability to stock carbon. Additionally, maintaining Eucalyptus plantations and natural forest is possible and desirable to supply carbon stock and to provide carbon services in heterogeneous landscapes.

Conclusions

This study showed that not necessarily more forest cover implies higher carbon stock at catchment scale. The case of Eucalyptus silviculture deserves special attention because we found that this land-use can favor the carbon stock in the whole catchment. Nonetheless, to unravel the real role of silviculture in the provision of global carbon services in reforest-oriented landscapes is necessary to develop more studies evaluating the variation in the carbon stock along the lifecycle of silvicultural products. Regarding natural forests, it is recommended that management decisions should be focused on the enrichment of natural forest remnants to increase their capability to stock carbon.

Acknowledgments

We thank National Geographic Society Committee for Research and Exploration (Grant #CP-080ER-17) and also by the Coordination for the Improvement of Higher Level -or Education- Personnel (CAPES-PROEX) by the financial support of fieldwork. C.Z.R was supported during the PhD fellowship by the Brazilian Ministry of Education (CAPES-DS, 2016–2019).

Supplementary Material

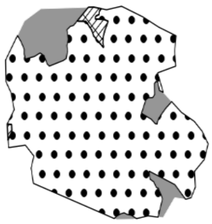
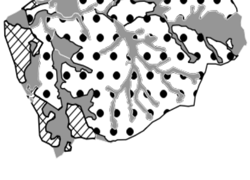
Equation S1. Developed by Burger & Delitti (2008)

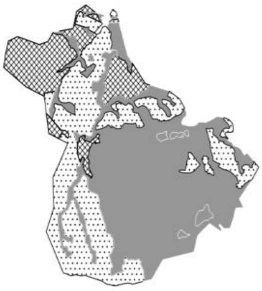
$$\ln B = -3{,}676 + 0{,}951 \times \ln d2 \times h$$

Where *B* is individual biomass, *d* is the diameters at breast height and *h* is the heights of trees.

Table S1. The fourteen catchments, natural forest cover and silviculture.

Continuous fill represents natural forests, dotted fill represents forestry and line fill represents grasslands.

Catchment Figure	Area (ha)	Forest cover (%)	Silviculture (%)
	170.51	11.51	86.75
	308.17	14.74	56.07
	892.52	30.73	59.41

Catchment Figure	Area (ha)	Forest cover (%)	Silviculture (%)
	6257.48	35.21	63.93
	984.15	44.80	54.78
	1225.19	53.71	32.19
	846.37	71.41	15.94

Catchment Figure	Area (ha)	Forest cover (%)	Silviculture (%)
	346.53	92.93	0.00

Table S1. Literature review of biomass values in Eucalyptus silviculture located in Brazil (from 1950 to 2019).

Reference	Title	State	Forest age	Carbon stock Mg ha^{-1}
(Schumacher et al. 2001)	Biomass estimate and nutrients content of an *Eucalyptus globulus* sub-specie maidenii stand	RS	4	41.5
		RS	3	28.28
(Santana et al. 2008)	Biomass estimation of Brazilian eucalypt plantations	SP	1	3.55
		SP	2	19.6
		SP	3	20.65
		SP	4	28.95
		SP	5	32.25
		SP	1	4.35
		SP	2	20.85
		SP	3	38.85
		SP	4	54.05
		SP	6	86.2
		SP	1	3
		SP	3	27.65
		SP	4	72.45
		SP	6	54.55
		SP	7	106.05

Reference	Title	State	Forest age	Carbon stock Mg ha^{-1}
(Ryan et al. 2010)	Factors controlling Eucalyptus productivity: How water availability and stand structure alter production and carbon allocation	SP	4	88.65
(Stape et al. 2010)	The Brazil Eucalyptus potential productivity project: influence of water, nutrients and stand uniformity in wood production	SP	6	84.98
		SP	3	25.82
		SP	5	58.09

Reference	Title	State	Forest age	Carbon stock Mg ha^{-1}
(Cabral et al. 2011)	Fluxes of CO_2 above a plantation of Eucalyptus in southeast Brazil	SP	2	38.54
		SP	3	56.82
		SP	4	83.92
(Gatto et al. 2011)	Carbon stock in the biomass of Eucalyptus crops in central-east region of the state of MG-Brazil	MG	2	16.88
		MG	3	27.50
		MG	4	39.64
		MG	5	51.66
		MG	6	63.40
		MG	7	74.67
		MG	8	85.21
		MG	9	94.97
		MG	10	103.08
(Campoe et al. 2012)	Stand level patterns of Carbon fluxes and partitioning in a *E. grandis* plantation across a gradient of productivuty, in SP state, Brazil	SP	6	64.5

Reference	Title	State	Forest age	Carbon stock Mg ha^{-1}
(Viera et al. 2012)	Biomass and nutrients in *Eucalyptus urograndis* stands in Serra do sudeste –RS	RS	2	9.25
(Wink et al. 2013)	The Eucalyptus age plantations influencing the Carbon stocks	RS	20	92.01
		RS	2	80.89
		RS	4	78.04
(Carvalho 2014)	Biomass and nutrients in an *Eucalyptus urograndis* stand set in sand soil in the Brazilian Southern	RS	4	37.46
(Cerruto Ribeiro et al. 2015)	Biomass and Carbon stock in Brazilian savanna and in a commercial stand of Eucalyptus in Minas Gerais state	MG	6	55.65

Table S2. Percentage of eucalypt stands by age in the 14 catchments.

Age of Eucalyptus stand	Percentage (%) of Eucalyptus stands
1	0.15
2	0.62
3	1.39
4	3.08
5	2.31
6	5.55
7	2.16
8	6.16
10	78.58

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Chapter 3

Proposal for the development of trade-off scenarios: carbon stock and paper provision in landscapes in a gradient of Atlantic forest and Eucalyptus plantations.

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Abstract

Most of the natural ecosystems around the world have been modified to give way to mosaics of different land-uses that aim to attend human demands. These changes can affect several ecosystem services simultaneously. It is important to evaluate the consequences for the future. One way to do that is to identify the trade-offs in scenarios based on drivers of change. In this study, we aimed to evaluate the potential trade-offs occurring between carbon stock and paper provision in landscapes with Atlantic Forest and Eucalyptus plantations. We created a simple conceptual model based on drivers that influence carbon stock and paper provision. Then, we constructed possible scenarios to simulate the response of the two esosystem services to harvesting events and variable forest cover at catchment scale. The results showed that the impermanence of carbon stock in Eucalyptus is responsible for the occurrence of trade-offs. We found that trade-offs occur in landscapes with approximately 30% of forest cover with values of carbon stock and paper provision around 20Mg ha^{-1}. We discuss possible management alternatives for landscapes mainly covered by natural forest and silviculture. The enrichment of the natural forest, the regulation of the harvesting schedule and the permanence of some of the stands whie other are harvested are among the management options.

Keywords: Silviculture harvesting, multiple services, ecosystem services, catchments management.

Resumo

Grande parte dos ecossistemas naturais ao redor do mundo foi modificada para dar lugar a mosaicos de diferentes usos da terra que visam atender às demandas humanas. Essas mudanças podem afetar simultaneamente vários serviços ecossistêmicos sendo necessário avaliarmos as consequências para o futuro. Uma maneira de avaliar isso é identificando trade-offs em cenários baseados em drivers de mudança. Neste estudo, objetivamos avaliar os trade-offs possíveis entre estoque de carbono e fornecimento de papel em paisagens cobertas por Mata Atlântica e plantios de eucalipto. Criamos um modelo conceitual simples a partir de fatores que influenciam o estoque de carbono e a provisão de papel. Em seguida, construímos cenários possíveis para simular a resposta dos dois serviços ecossistêmicos a eventos de corte da silvicultura em diferentes coberturas de floresta na escala de bacia. Os resultados mostraram que a impermanência do estoque de carbono no eucalipto é responsável pela ocorrência de trade-offs. Nós encontramos que os trade-offs ocorrem em bacias com aproximadamente 30% de floresta e valores de estoque de carbono e provisão de papel em torno de 20Mg ha^{-1}. Para concluir, nós discutimos possíveis alternativas de manejo para paisagens principalmente cobertas por floresta e eucalipto. O enriquecimento da floresta natural, a regulação do cronograma de

corte, a permanência de alguns talhões em quanto outros são cortados; são apenas algumas das opções.

Palavras-chave: corte de eucalipto, serviços múltiplos, serviços ecossistêmicos, manejo de bacia hidrográfica.

Introduction

Human activities have substantially altered land-cover, threatening the continuity of global natural processes and ecosystem services (ES) (Costanza et al. 1997; Alcamo et al. 2005; MEA 2005; Fu et al. 2015). One important way that land-use and land-cover change (LULCC) impacts on ES is disturbing the relationships between them and producing undesirable trade-offs (Yang et al. 2018). Maximizing the use of one ES can lead to the decline in another potentially inducing an irreversible change in the landscape (Fu et al. 2015). Evaluating multiple ES and the potential trade-offs at adequate spatial scales can guide regional ecosystem management (Yang et al. 2018). Environmental planners and managers have to find multi-objective land-management strategies aiming at ES maximization while minimizing trade-offs (Bradford and D'Amato 2012). Also, they should consider the effects of trade-offs that occur over large spatio-temporal scales; being some of them irreversible (Rodríguez et al. 2006; Xiangzheng et al. 2016).

The relationships between ES and LULCC are increasingly being recognized by researchers and international groups with a focus on ecosystem restoration, management, and conservation (Crossman et al. 2012; Fu et al. 2015; Xiangzheng et al. 2016). In that context, The Millenium Ecosystem Assessment created the Scenarios Working Group to understand possible futures of ES in a changing world

(Carpenter et al. 2006). Scenario analysis enables depicting the impacts of alternative policies and management strategies that may help to achieve conservation goals (Kok et al. 2017). Scenarios analysis and retrospective assessments of current ES supply using temporal analyses are recognized as methodological approaches to understanding ES associations (Nelson and Daily 2010; Lautenbach et al. 2011). Nonetheless, ES trade-offs are rarely considered in the construction of scenarios, weakening the ability of this tool to inform land-use policies (Yang et al. 2018).

The first step in an adequate process of scenario construction is the choice of the focal components and the definition of spatio-temporal boundaries of the system (Metzger et al. 2010; Rounsevell and Metzger 2010). Then, it is necessary to identify the drivers, i.e., the ecological or human-induced factors that affect ecosystem structures and functions altering the provision of ecosystem services (MEA 2005). Drivers can influence the focal components both directly and. The final step is the formulation of scenarios by modifying the conditions of the drivers and exploring the responses of the focal components.

Scenarios must be of low complexity, explicit and easy to understand for stakeholders and decision-makers (Olander et al. 2017). It is expected that the results of the scenario analysis may assist decision-makers to develop management options that perform adequately, irrespective of which of the future scenarios occur (Maier et al. 2016).

In this paper, we formulated short-term scale scenarios to understanding the relationship between carbon stock and paper provision in catchments within a gradient of natural forest and silviculture. We focused on the trade-offs between these two ES and the final purpose is to provide insights for decision-makers on possible strategies that minimize this trade-off.

Methods

Study area and ES estimates

We described the study area, data collection and the calculations of carbon stock at a catchment scale in Chapter 2 (See Equations 1-5). We used the same fourteen catchments of the Paraiba Valley and the current carbon stock and paper production services as a baseline scenario. We calculated the paper provision at a catchment scale multiplying the average volume of paper produced by hectare in Brazilian Eucalyptus plantations (40 Mg ha-1; Silva et al. 2015) by the area occupied by silviculture stands older than 5 years, which is the harvesting age for paper in Brazil (Brazilian Institute of Trees-IBA 2019). We standardized the results by the total catchment area (Equation 1).

$$P_j = \frac{40 \times A_{pz}}{A_{tz}} \qquad \text{Equation 1}$$

Where P_z is the paper provision in the *z* catchment, A_z is the area of silviculture in harvesting age in each *z* catchment, and A_{tz} is the total area of the *z* catchment.

Conceptual model

We designed a conceptual model based on the Intergovernmental Panel of Biodiversity and Ecosystem Services- IPBES, Martinez-Vega (2017) and Buarque (2003). We included direct and indirect drivers actuating carbon stock and paper provision and the relationships between drivers and the landscape components.

Focal components

We choose two main focal components for the model of this study: a) the carbon stock in forest and silviculture (regulation ecosystem service) and b) the standing stocked wood suitable for paper production (provision service).

Drivers

We used the concept of a driver indicated by MEA (2005). Drivers exert pressures on the environment, causing changes in the initial state. The resulting alterations in the state of the environment over time can impact human well-being and may have implications for societal objectives (Albert et al. 2016). Based on the literature and peer's opinion[1], we defined that the direct driver is the LULCC (Sleeter et al. 2018; Pellikka et al. 2018) and the indirect drivers are: public policies and institutions (Southworth et al. 2001; Manson 2006; Meyfroidt et al. 2013; Viña et al. 2016; Garrett et al. 2018), the silviculture harvesting pattern (Nunery and Keeton 2010; D'Amato et al. 2011), the demand for silvicultural products (Meyfroidt et al. 2013) and the prices of silvicultural product (Meyfroidt et al. 2013; Sohngen and Tian 2016).

Assessing the LULCC temporal dynamic

We assessed the temporal dynamic of the LULCC in the region by mapping 500 meters buffers from the edge of the eleven randomly selected forest fragments. We

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[1] Two members of the advisory committee of the main author, members of the research group, and the second author of this paper.

mapped the land-use/cover of the past using cloud-free Landsat-5 TM images of the region dating from 1982. The current land-use/cover map is the same we made in Chapter 2 (See Methods). We overlaid both past and present land-use/cover maps and identified the areas with or without changes and the type of changes when it occurred. We evaluated the LULCC considering the whole sampled area and calculating the changes (and no changes) of each land-use/cover type.

Scenarios construction

We developed exploratory scenarios according to the Intergovernmental Panel of Biodiversity and Ecosystem Services -IPBES classification of scenarios (IPBES 2016). We used the LULCC as the direct driver of change in the carbon stock and the in the paper provision. In this study, the LULCC consists of the forest cover changes and the silviculture cover changes. On the one hand, we selected the harvesting pattern as the main driver of silviculture cover changes. On the other hand, we included the forest cover changes using the catchments in a gradient from 10 to 100% of forest cover. Both forest cover changes and silviculture cover changes enclose the influence of other indirect drivers as public policies and institutions (Southworth et al. 2001; Manson 2006; Meyfroidt et al. 2013; Viña et al. 2016; Silva et al. 2017; Garrett et al. 2018). It is important to mention that we included an additional exploratory scenario considering that Brazilian paper stocks 50% of the carbon originally stocked in the Eucalyptus biomass (Silva et al. 2015).

The scenarios did not aim to represent temporal successions, but they intended to elucidate the impacts of different harvesting patterns in the 14 catchments with different percentages of natural forest cover. In all scenarios, we assumed that removing Eucalyptus stands does not impact directly the carbon stock in the natural forest.

Threshold test of carbon stock along forest cover gradient

We used the *piece-wise* function to test the existence of a threshold in the carbon stock in response to a reduction in the natural forest cover along the gradient of the catchments (See Toms and Villard 2015; Peng et al. 2017). We used the software R. 2.18 to perform the test.

Trade-offs between carbon stock and paper provision

We used the carbon stock and paper provision tendencies resulting from the scenarios to identify possible trade-offs. Then, we identified the land-use/cover combination between natural forest and silviculture capable to maintain both services. For the trade-off identification, we followed the next steps:

Step 1 We used the method presented in Lang & Song (2018). The authors proposed the use of the *production possibility frontier model* to analyze the relationship between pairs of ES. This model is widely used in economics and is a visual representation that shows the scarcity and selectivity of resources and provides the optimal combination between them to produce two commodities (Lang and Song 2018). In this study, we considered the catchment area as a scarce resource that can be used for maintaining natural forest or planting Eucalyptus. We represented the production possibility frontier model to all the proposed scenarios.

Step 2 We explored the relationship between carbon stock and paper provision regarding the forest cover percentage in catchments in each scenario.

In all the scenarios, we used the graphical representation of tendencies and the crossing point between the carbon stock and the paper provision to identify the land-use/cover combination of forest and Eucalyptus able to maintain both ES. In that land-use/cover combination, the trade-offs are minimized and the provision of both services is equalized. We presented the standard error and coefficient of determination in the graphics.

Results

Conceptual model

Figure 1 presents the conceptual model of this study case including the direct and indirect drivers that influence the carbon stock and paper provision. This model is not a closed and isolated system, for that reason, we included natural inputs and waste to simply recognize the it is an open system. Considering Pellikka (2018) and Sleeter (2018), we selected the LULCC as the main direct driver of changes in carbon stock and paper provision.

LULCC are influenced by public policies and institutions because they may regulate the natural forest protection but may also favor the reduction in the forest area (Southworth et al. 2001; Manson 2006; Meyfroidt et al. 2013; Viña et al. 2016; Garrett et al. 2018). Public policies and institutions also influence silviculture by controlling the creation of new areas and by regulating harvesting patterns as Silva et al (2017) identified in the same region of this study. For that reason, we considered public policies and institutions as indirect drivers in the conceptual model.

Two drivers that can influence the silviculture cover changes are the demand and the price of the paper. Mayfroidt (2013) and Sohgen (2016) assessed how drivers located outside of the local landscape (e.g. market dynamics) can influence the land-use/cover in a region. Mayfroidt particularly mentioned Brazil as one of the countries that have absorbed the growth in global demand for palm-oil resulting in logging expansion and lost forest cover (Meyfroidt et al. 2013). It can be also the case of paper and pulp since Brazil is a global player for these products (Brazilian Institute of Trees-IBA 2019).

Silviculture cover is directly influenced by harvesting. Thus we propose harvesting as one of the indirect driver of change in carbon and paper provision. D’amato (2011) and Nunery (2010) used simulation and scenarios of silvicultural practices and also found that harvesting patterns affect the carbon stock. Lastly, according to Wilson & Wilson (2001) silviculture harvesting is also influenced by price and demand for silvicultural products. Increases in the price of silvicultural products and expansions in the national and international demands (e.g., China´s economic boom) tend to incentivize and accelerate the production.

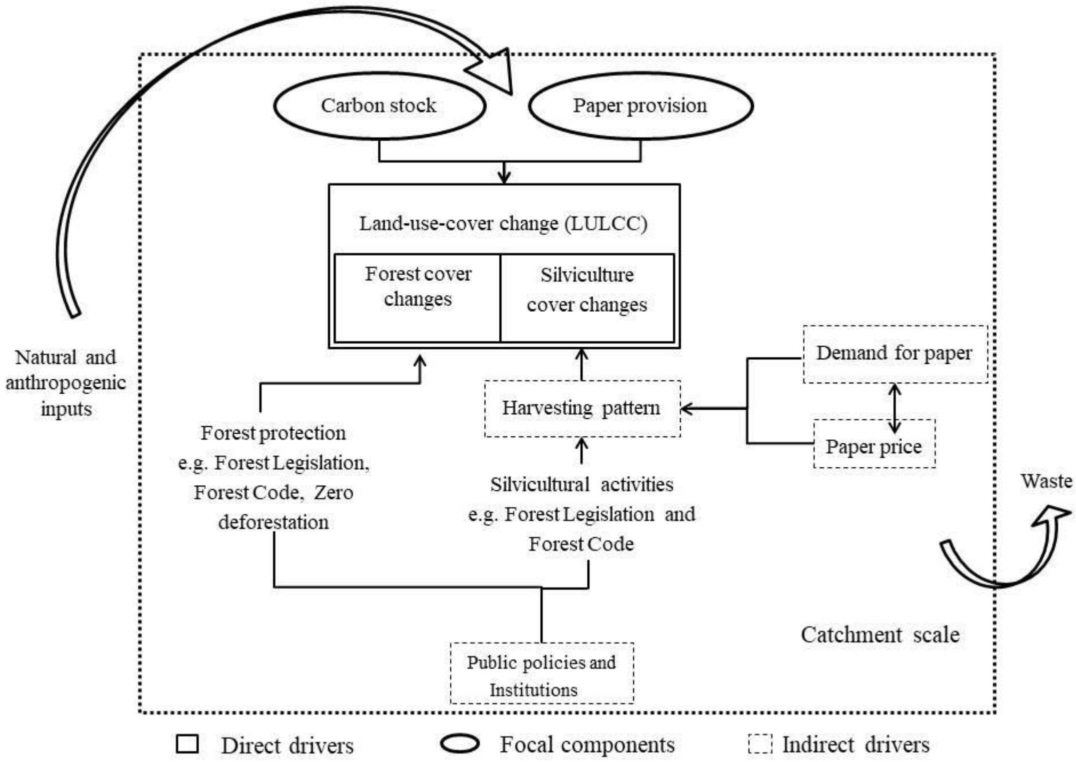

Figure 1. Conceptual model of drivers influencing carbon stock and paper provision in catchments occupied by a gradient of forest cover and silviculture.

LULCC temporal dynamic

Temporal tendencies could be used to evaluate future trajectories in the land-use/cover of a region (Berenguer et al. 2014; Wandelli and Fearnside 2015). Therefore, we evaluated approximately four decades of land-use/cover temporal changes in the study area. In 1982, the sampled area of the study region was covered by 72.01% of natural forest and 1.32% of silviculture. Currently, natural forest covers 55.52% while silviculture covers 6.6%. This is a reduction of 16.49% in the natural forest area and an increase of more than 5% in the silviculture area (Figure 2b and 2c). Figure 2a shows the percentages of losses, gains, and maintenance relative to the area of each land-use/cover type (forest, silviculture, and pasture) comparing 1982 with 2018. Our estimates indicate that the silviculture area is four times larger than was in 1982.

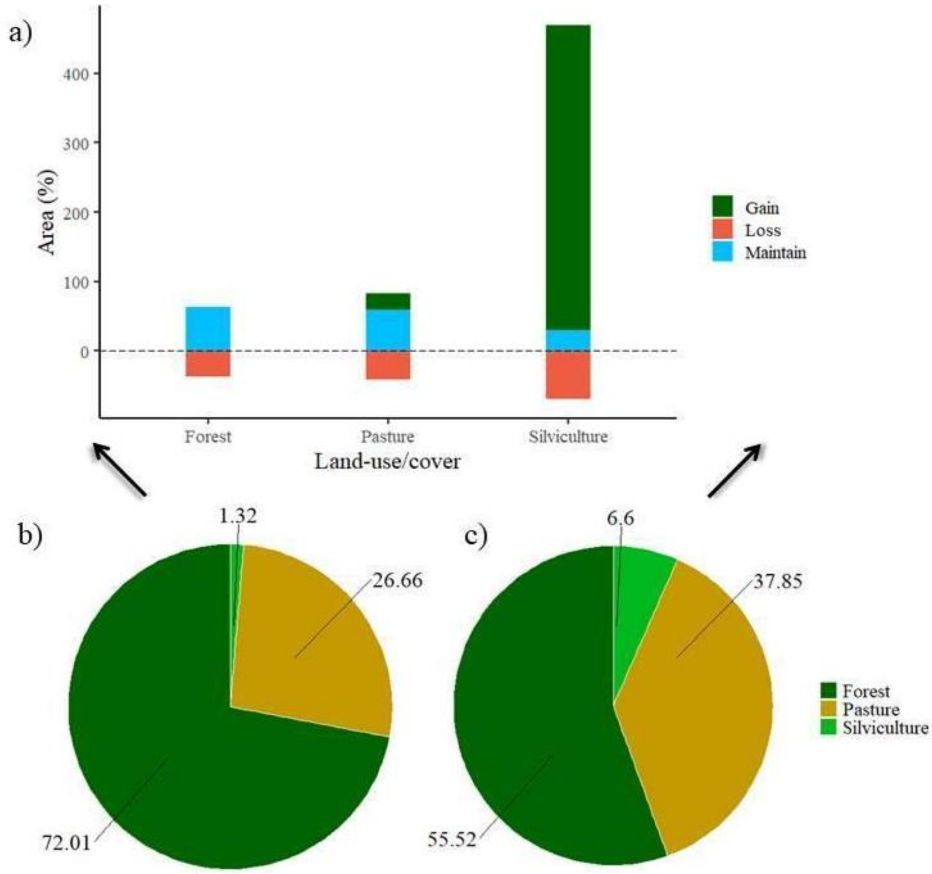

Figure 2. a) Changes in the area relative to each type of land-use/cover between 1982 and 2018, b) percentage of total sampled area occupied by each type of land-use/cover in 1982 and c) percentage of total sampled area occupied by each type of land-use/cover in 2018.

Considering only the natural forest loss, we find that 82% was transformed into pasture and 17% into silviculture, while the gain was 94% from pasture and 6% from silviculture. Regarding silviculture, an alarming result is that 75% of the silviculture area gain comes from natural forests. Nonetheless, silviculture also was replaced by forest (62% of the silviculture losses). In sum, the LULCC dynamic resulted in net gains of silviculture over natural forest areas, but the natural forest still is the principal land-cover of the region.

Threshold test

Figure 4 shows that there is no breaking point in the positive relationship between the percentage of forest cover and the carbon stock in the natural forest at a catchment scale. Therefore, we find no evidence of a threshold between them.

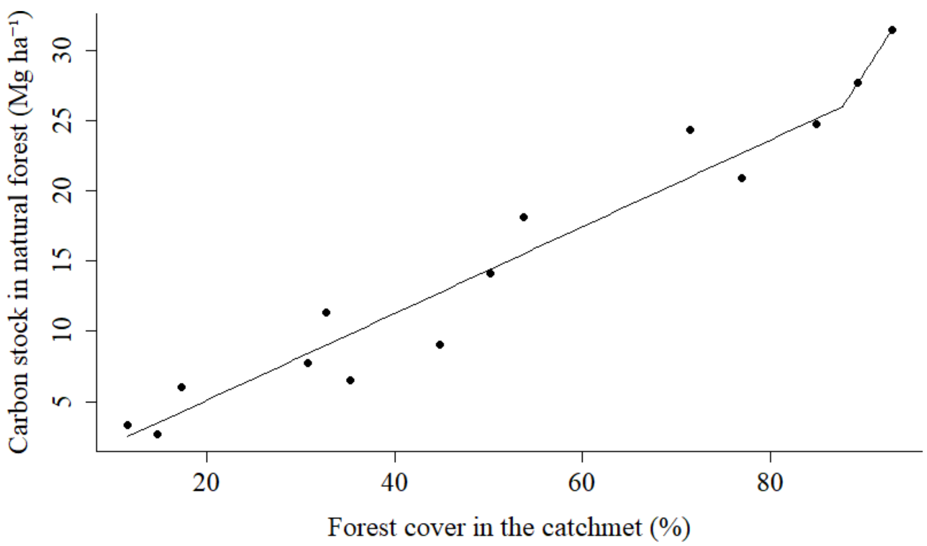

Figure 4. Piece-wise test for the threshold of the carbon stock in the natural forest in relationship with the forest cover percentage in the catchments.

Scenarios and trade-offs

We propose one baseline scenario and four additional scenarios considering silviculture harvesting events and a gradient from 10% to 100% of natural forest cover at a catchment scale. Table 2 describes each scenario and details the contribution of natural forest and silviculture to the carbon stock and the contribution of silviculture to paper provision.

Table 2. Description of the scenarios based on silviculture harvesting events for the 14 catchments.

Scenario	Forest contribution to carbon stock	Silviculture contribution to carbon stock	Silviculture contribution to the paper provision
1. Baseline	Carbon stock estimated in the initial and intermediate-advanced natural forest area in each of the catchments	Eucalyptus stands of all ages found in the catchments	Due to the fact that we did not find harvested eucalyptus stands, there is no paper provision.
2		All the Eucalyptus stands are in the harvesting age (5-6 years).	All the eucalyptus stands are in the harvesting age (5-6 years), but they are not being harvested yet to produce paper. Thus, there is no paper provision.

Scenario	Forest contribution to carbon stock	Silviculture contribution to carbon stock	Silviculture contribution to the paper provision
3	Carbon stock estimated in the initial and intermediate-advanced natural forest area in each of the catchments	Only the Eucalyptus stands with less than 6 years of age are stocking carbon (7.4% of total Eucalyptus stands in all the catchments). Eucalyptus stands with more than 6 years of age are harvested to produce paper (92.4% of total Eucalyptus stands in all the catchments).	Eucalyptus stands with more than 6 years of age are harvested to produce paper.
4		All Eucalyptus stands were in the harvesting age (5-6 years) and are harvested to produce paper. Then, none of them is stocking carbon.	All Eucalyptus stands were in the harvesting age (5-6 years) and are harvested to produce paper.

Scenario	Forest contribution to carbon stock	Silviculture contribution to carbon stock	Silviculture contribution to the paper provision
5	Carbon stock estimated in the initial and intermediate-advanced natural forest area in each of the catchments	Only the Eucalyptus stands with less than 6 years of age are stocking carbon (7.4% of total Eucalyptus stands in all the catchments). Eucalyptus stands with more than 6 years of age are harvested to produce paper (92.4% of total Eucalyptus stands in all the catchments)[2]. However, 50% of the carbon originally stocked in the Eucalyptus biomass remains in the paper.	Eucalyptus stands with more than 6 years of age are harvested to produce paper.

[2] Acording to Silva en the LCA of paper in Brazil, 50% of C remains stock in paper.

Scenario 1- Baseline

Figure 4 shows the current land-use/cover condition in our study area. Presently, 78.58% of the Eucalyptus stands surpassed the typical rotation time for paper production in Brazil (5-6 years). In consequence, the carbon stock in these stands is higher than expected for plantations intended to produce paper. Figure 4 shows that the total carbon stock tends to decrease from approximately 50 Mg C ha^{-1} to 35 Mg C ha^{-1} along the gradient of natural forest cover. Also, the carbon stock is highly variable in catchments with low natural forest cover and the variability is reduced in catchments with more than 50%. of forest cover. Since paper is not being produced at this time, there is no trade-off between the two ES.

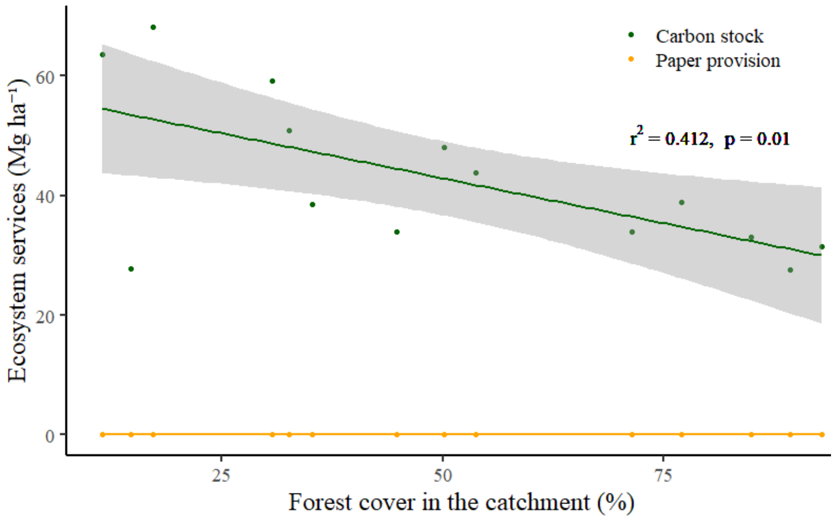

Figure 4. Carbon stock and paper provision along a gradient of natural forest cover in the catchments in baseline scenario 1. Linear best fit has been added to the carbon stock data.

Scenario 2

Figure 5 shows the results of scenario 2 where all Eucalyptus stands in the catchments are assumed to be at the end of the first rotation cycle (5-6 years), but they are not being harvested yet. Total carbon stock tends to decrease along the natural forest cover gradient from approximately 40 MgC ha-^{1} to 32 MgC ha^{-1}. The carbon stock is more variable in catchments with low natural forest cover than in catchments with more than 50%. of forest cover. As expected, the total carbon stock in scenario 2 is lower than scenario 1. This is explained by the simulated average reduction in the age of Eucalyptus stands compared with baseline scenario 1.

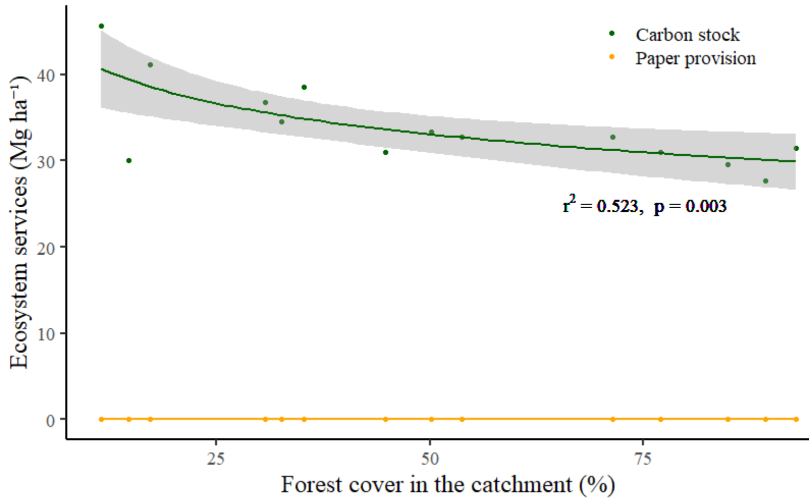

Figure 5. Carbon stock and paper provision along a gradient of natural forest cover in the catchments in scenario 2. Logarithmic best fit has been added to the carbon stock data.

Scenario 3

Scenario 3 is the first of our scenarios where the Eucalyptus are assumed to produce paper. Figure 6a) shows that there is a linear inverse relationship between the carbon stock and the paper provision. We find a trade-off between carbon stock and paper provision. Levels of paper production above 20 Mg ha^{-1} tend to reduce the carbon stocked at minimum levels. The carbon stock is highly variable in catchments with low natural forest cover and the variability is reduced in catchments with more than

50%. of forest cover. Figure 6b) shows that in this scenario the crossing point between carbon stock and paper provision tendencies occurs approximately when 30% of natural forest cover is maintained. Matching Figures 6a and 6b allows finding the maximum quantities of the two ES per area is reached when the natural forest cover is approximately 30% in the catchment. At this point, the trade-off is minimized and the provision of both ES is equalized.

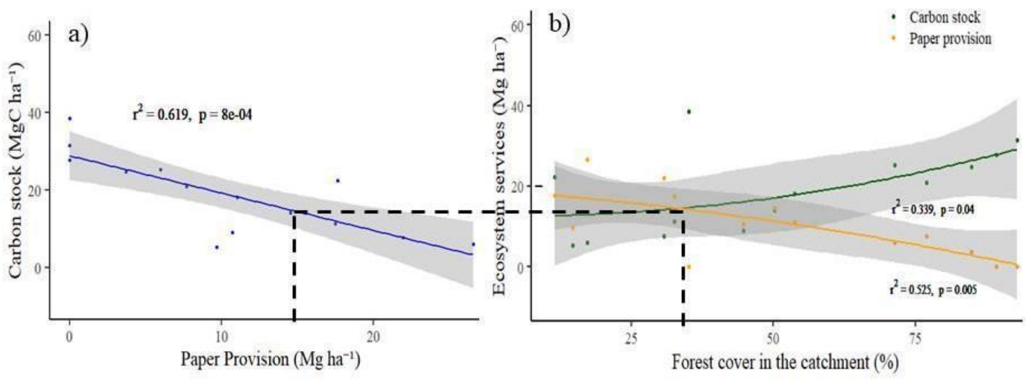

Figure 6. a) Trade-off between carbon stock and paper provision in scenario 3. Linear best fit has been added. b) Carbon stock and paper provision along the forest cover gradient. Quadratic best fits have been added to the carbon stock and paper provision tendencies respectively.

Scenario 4

We also find a trade-off between carbon stock and paper provision in scenario 4. Figure 7a) shows that there is a linear inverse relationship between the carbon stock and the paper provision. In this scenario, the impact of paper production on carbon stock is higher than in scenario 3 because all of the Eucalyptus stands were in the harvesting age and, indeed, harvested to produce paper. In this case, paper production levels above 15 Mg ha^{-1} tends to reduce the carbon stocked in the catchment to almost zero. In this scenario, the variability in carbon stock in the catchments along the gradient of natural forest cover is lower than the variability found in the previous scenarios even in catchments with less forest cover. Figure 7b) shows that the crossing point between the two ES tendencies occurs approximately when 50% of natural forest cover is maintained. Matching Figures 7a and 7b allows finding the maximum quantities of the two ES per area is reached when the natural forest cover is approximately 50% in the catchment.

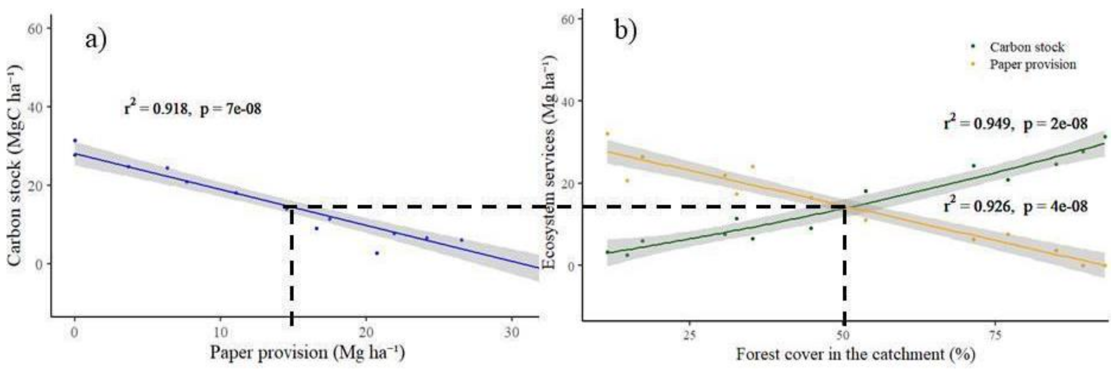

Figure 7. Trade-off between carbon stock and paper provision in scenario 4. Linear best fit has been added. b) Carbon stock and paper provision along the forest cover gradient. Linear best fits have been added to the carbon stock and paper provision tendencies.

Scenario 5

This exploratory scenario 5 considers that 50% of the carbon originally stocked in the Eucalyptus biomass remains within the paper. In this case, we found no significant trade-off between carbon stock and paper provision. Figure 8a) shows that the inverse relationship between carbon stock and paper provision is weak the slope of the curve approaches zero. Scenario 5 could be useful because -even when the carbon stock in the area is highly reduced as a result of the production of paper (See scenarios 3 and 4)- if we account for the carbon that remains stocked in the paper, the net carbon stock losses are slightly compensated. Figure 8b) shows that there is a crossing point between the two ES tendencies and occur approximately when 20% of natural forest cover is maintained. However, the carbon stock tendency is not statistically significant.

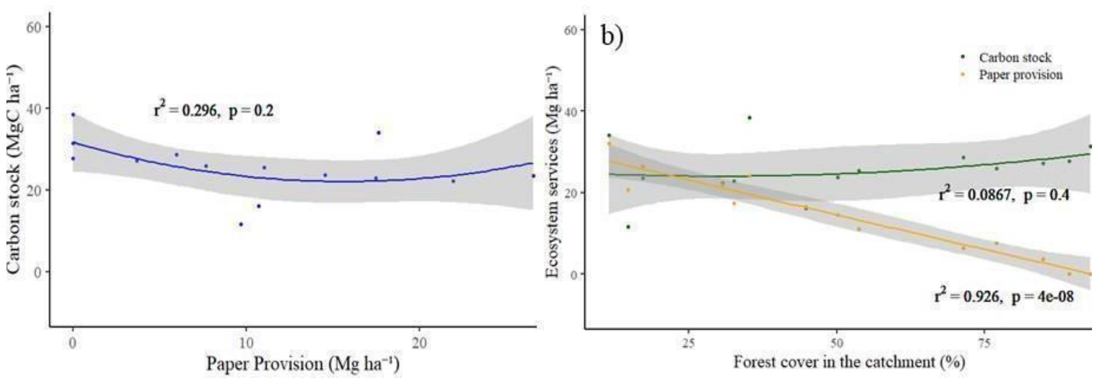

Figure 8. Trade-off between carbon stock and paper provision in scenario 5. Quadratic best fit has been added. b) Carbon stock and paper provision along the forest cover gradient. Quadratic and linear best fits have been added to the carbon stock and paper provision tendencies, respectively.

Discussion

This study is an attempt to elucidate the dynamic relationship between two ES in landscapes with forest and silviculture in different quantities. It is among the few studies attempting to guide future planning of natural ecosystems considering temporal variations on the provision of ES and evaluating silvicultural harvesting scenarios from an ES view in a tropical region (Ranatunga et al. 2008; Diaz-Balteiro et al. 2009; Antón-Fernández and Astrup 2012). Starting with a conceptual model, we formulated possible scenarios where carbon stock and paper provision take different paths. The silviculture harvesting pattern and the quantity of forest cover in the landscape influence directly in the carbon stock and paper provision at a catchment scale. Thus we explored scenarios including variation in these two factors.

Our results of the LULCC in the study region comparing 1982 with 2018 have two coincidences with the results of Silva et al (2016) that also studied the LULCC in the Paraiba Valley from 1985 to 2011 and the driving forces influencing those changes. The first coincidence is that they also found that most of the increases of the forest area were at the expense of pasture lands. The second is that they found similar values for silviculture area. Nonetheless, we estimated that most of the losses of natural forest area were converted in silviculture but Silva (2016) indicated that most of the Eucalyptus stands in the Paraiba Valley were established in areas of degraded pastures. One reason for these divergences is that the time-lapse that we analyzed could hide the changes occurring in the shortest periods of time. Another reason is that the authors studied the forest cover gains along the total Paraiba Valley region and by Municipalities, but we sampled only local areas around our study region. Some specific processes may occur at the local scale and could be neglected when the analyses are performed in lower spatial resolutions. In any case, both results could be important for different environmental and management strategies.

Based on the conceptual model we evaluated five different scenarios considering silviculture harvesting pattern in catchments with different forest cover quantities. In other contexts, e.g., other regions of the Brazilian Atlantic Forest or even in the same region but in catchments with different landscape composition, silviculture harvesting patterns may not be the most important driver to consider and other factors (e.g., new environmental policies or climate change) should be included in the development of scenarios.

Comparing the results of the five scenarios proposed in this study could provide insights for decision-makers. Baseline scenario-1 and 2 show the high potential of Eucalyptus (>5 years old) to stock carbon in the study region, even more than the intermediate-advanced forest. However, at the expense of paper provision and the economic benefits associated. We have already discussed the possible causes explaining this finding in chapter 2. In any case if Eucalyptus stands are permanently excluded from the paper provision circuit, they become an interesting option for conservation ends like carbon offsets (See Hartley 2002). Nevertheless, as multifunctional landscapes are desired, the paper provision cannot be neglected.

Scenarios 3 to 5 consider both carbon stock and paper production. The identification of trade-offs and the most favorable composition of natural forest and silviculture showed that scenario 3 could be considered as the most favorable in terms of both ES. Harvesting only Eucalyptus older than 5 years permit that the Eucalyptus with less than 5 years continues contributing to the carbon stock in the catchments. Hence, catchments with smaller percentages of forest cover never reach a levels close to zero of carbon stock. This is not the case of scenario 4 because all the Eucalyptus that were in the harvesting age were harvested to produce paper at the same time.

The quantities of carbon stock and paper provision found in the crossing points in scenarios 3 and 4 are very low for both services. In the case of carbon stock, the values are not higher than the carbon stock that we found in the intermediate-advanced forest. For paper provision, the value is approximately 50% of the current performance of paper production per hectare in Brazil (40 Mg ha^{-1}). This is important because our analyses are restricted to physical quantities (e.g., Mg ha^{-1}) and important indirect drivers such as the prices of paper, prices of land, carbon price, etc are neglected. It is likely that economic incentives, subsidies, among others shall be required to achieve a hypothetical optimal economic-ecologic-efficiency. Further research is required on these important topics.

Scenario 5 is important to understand that carbon stock is also a regulation ES on a global scale. Also, it is important to recognize that the carbon stocked within the paper represents an impermanent stage (Sedjo 2001; Yue et al. 2017). Eventually, the paper will be degraded releasing the carbon to the atmosphere. Recycled paper requires less energy and emits less CO_2 than new paper produced (Turner, 2015), but it is not possible to recycle *at infinitum*. Most of the paper produced in Brazil (10% paper, 89% pulp; (EMBRAPA 2019) is exported to Latin America, Europe and North America (MDIC – Ministry of Development Industry and Trade 2013). Clearly, the process of exportation results in carbon emissions that should be accounted for the carbon stock balance (e.g, transportation emissions).

Finally, according to our results of all scenarios, catchments with more forest cover present less variability in the carbon stock and catchments with less forest cover preset lower variability in the carbon stock in conditions where only the natural forest contribute to the carbon stock. This result suggests that the presence of natural forest cover provides stability to the carbon stock at a catchment scale.

Management options for catchments mainly occupied by silviculture could include the establishment of a harvest schedule to balance the age distribution between stands, considering the carbon stock in the neighbor's initial and intermediate-advanced natural forest. When one stand of Eucalyptus is harvested, others stands continue stocking carbon together with the natural forest until reaching the harvesting age.

As suggested by Silva et al (1995), Brancalion (2019), Amazonas, (2018), other management possibilities, are mixed schemes with Eucalyptus and natural forests as a restoration strategy for degraded lands. Moore (2012) and Lundmark (2018) proposed the regulation of harvesting frequencies and practices of retention levels applied to conventional and innovative silvicultural systems. These options would probably require an institutional framework with new environmental policies that regulate silvicultural activities.

Depending on the silvicultural management practices, plantations can harbor some wild species when understory elements are retained into the stands (Brockerhoff et al. 2013). At a landscape scale, having natural forests around Eucalyptus plantations is also beneficial not only for biodiversity but also for maintaining connectivity and structural complexity (Brockerhoff et al. 2013). Some studies found beneficial effects of mixed planted forests that no necessary need to be implemented at the stand level to be effective, only adjacency to native vegetation could result in positive effects in ecological functions (Brockerhoff et al. 2013). In addition, we suggest the inclusion of other ecosystem services and socioeconomic aspects into the carbon stock and paper provision perspectives. For example, (Farinaci 2012) identified socio-cultural negative impacts of Eucalyptus silviculture in the Paraiba Valley in spite of the environmental impacts that are still controversial.

The methodologies used in this study pretend to provide a straightforward framework for assessing carbon stock in catchments with natural and planted forests. Conceptual models such as presented in this study are essential as communicative tools that help to integrate different approaches in a coherent overall picture (Haberl et al. 2009). The model we proposed did not use mathematical representations and not even involved other stakeholders. Nonetheless, we hope that this model will help to understand the interdependencies around carbon stock and paper provision at a local scale. We consider that different stakeholder's participation in model construction is an important next step to clarify and properly understand the dynamic process occurring in landscape management.

Conclusion

The results of this study show that scenario analysis is an appropriate tool to provide insights into the relationships between ES occurring at a landscape scale, Catchments with higher percentages of Eucalyptus cover usually have more carbon stock. Nevertheless, the impermanence of carbon stock in Eucalyptus silviculture promotes the occurrence of trade-offs between carbon stock and paper provision. The findings of this study point out that equalization of both ES occurs at very low values of both ES and in catchments with approximately 30% of forest cover. An implication of this is the need to adopt management strategies that enrich the natural forest and promote the permanence of some of the stands during harvesting. In spite of its limitations, the study certainly adds to our understanding of the relationships between ES and provides visualization of possible futures that may help policymakers to make better decisions.

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Abstract

Tropical landscapes have experienced many and rapid changes that simultaneously affect several ecosystem services. The absence of strong policies about land-use and land-cover may result in undesirable consequences. Tropical forest landscapes provide several ecosystem services and carbon stock is considered among the essential for global climate regulation. The replacement of natural forests produce changes in the carbon stock and potentially increase the atmospheric CO_2 concentrations. Conversely, silviculture areas are important for meeting societal demands, but silvicultural production may result in negative environmental impacts at different scales. Hence, environmental planners should focus on finding strategies that maximize the ES while minimizing trade-offs in heterogeneous landscapes. In order to reach this target, it is urgent to obtain accurate estimates of carbon sequestration and stock at appropriate spatial scales. Also, it is necessary to understand the real contribution of each land-use and land-cover type to the total carbon stock. Then, the development of scenarios could permit the identification of potential trade-offs and the associated negative impacts on the regulation and provisioning services that will impact different stakeholders. With this in mind, we aimed at identifying how the reduction of natural forest cover and the increase of *Eucalyptus* plantations affect the carbon stock (regulation ecosystem service) and paper provision (provision ecosystem service). For that, (i) we evaluate the differences between biomass values from the Pantropical Aboveground Biomass Density Map (PABDM) and field-based estimates in Brazilian Atlantic Forest fragments. Then, we explore the possible causes for the results of the comparisons and discuss the consequences for environmental planners (chapter 1). (ii) We analyze how the reduction in natural forest cover and the expansion of silviculture affect the carbon stock at the catchment scale. We studied fourteen catchments with a gradient of natural forest and Eucalyptus from 10% to 100% of forest cover. We estimated the aboveground biomass of the forests in the fieldwork and carried out a literature survey of the carbon stock in Brazilian Eucalyptus plantations of different ages (chapter 2); Finally (iii) we identify the potential trade-offs between carbon stock and paper provision in the catchments within the gradient of natural forest cover. We designed a simple conceptual model of drivers and formulate possible scenarios to evaluate the impacts of the main drivers in the carbon stock and paper provision. Our main overall results are: (i) AGB estimates from PABDM maps range 1.2 to 24 times higher than the field-based estimates, evidencing that great attention is needed when using these sources of information in political decision-making; (ii) there are lower carbon stocks in the natural forest than the in silviculture, probably due to the historical human interference on the forest, plus the unexpected producers' decision to not cutting the Eucalyptus; (iii) scenarios showed the impermanence of carbon stock in Eucalyptus as the principal responsible for the occurrence of ecosystem services trade-offs. This effect arises at values around 20 Mg ha^{-1} of carbon stock and paper provision and with occurs in catchments with approximately 30% of natural forest cover.

Keywords: Aboveground Biomass; Regulating Services; Forest Fragments. Silviculture; Tradeoffs; Scenarios.

Resumo

Paisagens tropicais tem experimentado muitas e rápidas mudanças que afetam simultaneamente vários serviços ecossistêmicos (SE). Na ausência de fortes políticas preventivas, as decisões sobre o uso e a cobertura da terra ao podem ter consequências indesejáveis. As paisagens de florestas tropicais fornecem vários serviços ecosistemicos, dentre os quais o estoque de carbono é considerado como essencial para a regulação climática global. A substituição de florestas naturais gera mudanças no carbono estocado e potencialmente aumenta as concentrações de CO2 atmosferico. Por outro lado, áreas com silvicultura são importantes para atender demandas da sociedade porem, a produção silvicultural pode resultar em diversos impactos negativos em diferentes escalas espaciais. Entre tanto, planejadores ambientais deberíam focar em encontrar estratégias que maximizem os SE ao mesmo tempo que minimizem os trade-offs em paisagens heterogêneas. Para atingir este objetivo é urgente a obtenção de estimativas acuradas de sequestro e estoque de carbono em escalas espaciais adequadas. Ao mesmo tempo, também é necessario entender a contribuição real de cada tipo de uso e cobertura da terra.. Seguidamente, o desenvolvimento de cenários permitiria a identificação de trade-offs potenciais e dos impactos negativos nos serviços de regulação e de provisão que por sua vez irão impactar diferentes atores. Tendo isso em mente, nosso propósito foi identificar de que forma a redução na cobertura de floresta natural e o aumento de plantações de Eucalipto afeta o estoque de carbono (SE de regulação) e a provisão de papel (SE de provisão). Para isso, (i) nós evaluamos as diferenças entre valores de biomassa acima do solo apresentados no Mapa Pantropical de densidade de biomassa e estimativas baseadas e, trabalho de campo, em fragmentos de Mata Atlântica Brasileira. Depois, nós exploramos possíveis causas que explicassem as diferenças encontradas e discutimos as consequências para planejadores ambientais (capítulo 1). (ii) Nós analizamos de que forma a diminuição de cobertura de floresta natural e a expansão da silvicultura afetam o carbono estocado a escala de microbacia. Nós estudamos quatorze microbacias que formam um gradiente de de 10 a 100% de cobertura florestal e silvicultura. Nós estimamos no campo a biomassa acima do solo na floresta e realizamos uma revisão de literatura para o carbono estocado em plantações de Eucalipto de várias idades no Brasil. (capítulo 2). Finalmente (iii) nós identificamos trade-offs potenciais entre o estoque de carbon e a produção de papel nas bacias formando um gradiente de cobertura florestal e silvicultura. Nós desenhamos um modelo conceitual simples e formulamos possibeis cenários para avaliar os impactos das principais forças motoras no estoque de carbono e a provisão de papel. Os principais resultados são: (i) as estimativas AGB dos mapas do PABDM são 1,2 a 24 vezes mais altas que as estimativas baseadas em campo; então, é necessário muita atenção ao usá-las para tomada de decisões políticas; (ii) O estoque de carbono é mai baixo na floresta natural do que na silvicultura, provavelmente devido a histórica interferência humana sobre as floresta, adicionada à decisões inesperadas dos produtores sobre cortar ou não os eucaliptos; (iii) os cenários mostraram que a impermanência do estoque de carbono no eucalipto é a principal responsável pela ocorrência de tradeoffs de serviços ecossistêmicos. Os trade-offs ocorrem quando o estoque de carbono e a provisão de paper são aproximadamente 20 Mg ha^{-1} e esto ocorre em microbacias com em torno de 30% de cobertura florestal.

Palavras-chave: estimativas de biomassa, regulação climática, corte em silvicultura, tradeoffs, cenários.

General conclusion

Carbon stock estimates require attention, in special considering the spatial and temporal scale and the objectives of the study. Biomass maps that extend along with big areas, as regional or global maps could not be suitable for decisions at the local scale. In the case of degraded forests as the Atlantic Forest, there is a high variation in the carbon stock at the local scale that could not be detected in regional and global maps.

At catchment scale estimating carbon stock in each land-use/cover type may assist management decisions. Nonetheless, it is important to consider the temporal variation in the carbon stock, mainly when silviculture is an important component in the landscape. The carbon stock in silviculture is impermanent since planted forests are harvested to produce paper (or other wood-based products). It is highly recommended to consider that impermanence in management decisions when silviculture is present in the landscape.

One suitable method to understand the impermanence of carbon stock of silviculture is using scenario analysis. Visualizing possible futures may help to anticipate undesired results or maximize the benefits. Once we found that the equalization of both carbon stock and paper provision occurs at very low values of both ES and in catchments with approximately 30% of forest cover, management options are required to benefit different stakeholders.