Research Article
doi: 10.1590/01047760202329013164
vol(29), 2023

CERNE

Ecological patterns and conservation opportunities with carbon credits in Brazil nut groves: a study-case in the Southeast Amazon

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FOREST ECOLOGY

ABSTRACT

Background: Brazil Nuts (BN) tree is a species of high importance in Amazon region. Their continuous use by traditional communities is often related to disturbances that lead to larger degraded areas where this species is commonly found ("BN groves"). Here we aimed to explore the ecological patterns of BN groves vegetation and its relationship with BN trees and evaluate their potential as a source of carbon credits. We sampled 15 circular plots, with Brazilian Nut trees as the center (focal trees) and collected morphometric data from the focal trees. Additionally, we evaluated fruit production for a period of 5 years to obtain annual measurements, which were used as a proxy of the anthropic impact associated with the collection process. Through analysis of the data, we: i) examined the effects of BN trees on the adjacent vegetation; ii) quantified the potential amount of carbon credits in the adjacent vegetation and in the focal trees by converting carbon stock to equivalent CO_2.

Results: The adjacent vegetation structure was influenced by the size of BN trees (focal trees). No important effects of BN trees on the adjacent vegetation floristic composition and functional attributes were found. Additionally, we found that Brazilian Nut groves possess a significant potential for carbon credits that could be leveraged in the future carbon credit market,

Conclusion: The study highlights the potential for carbon credit generation in Brazil nut groves in the Southeast Amazon as a means of supporting conservation and restoration efforts in these environments.

Keywords: *Bertholletia excelsa* Bonpl; payment for environmental services; carbon trading; Castanhais; Brazil nut; forest bioeconomy; carbon market; forest biomass.

HIGHLIGHTS

Brazil Nut (BN) trees have an ecological effect in adjacent vegetation in BN groves.
BN trees surrounding vegetation may offer financial return by carbon credits sale.
Exploration of BN trees carbon-seeds financial returns may help in Amazon conservation.
BN groves may be important in nature-based solutions of carbon and non-timber forest products.

SOUZA, C.R.; BALDONI, A.B.; TONINI, H.; MAIA, V.A.; SANTOS, R.M.; LUVISON, M.; SANTOS, J.P. Ecological patterns and conservation opportunities with carbon credits in brazil nut groves: a study-case in the southeast amazon. CERNE, 2023, v.29, e-103164, doi: 10.1590/01047760202329013164

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Received: September, 15/2022 Accepted: January, 24/2023

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CERNE
ISSN 0104-7760
UNIVERSIDADE FEDERAL DE LAVRAS

INTRODUCTION

The intense deforestation and use of natural resources in Amazon Forest over the past decades increased the number of highly degraded areas underscoring the urgent need ecological restoration efforts (Aragão et al., 2014, Brancalion et al., 2016, Qin et al., 2019). "In this context, certain tree species that are legally protected by logging restrictions or possess economic value may still persist, while adjacent vegetation is partially or completely removed (Aragão et al., 2014, Scoles et al., 2016). These trees also remain as property limits or windbreak, while adjacent areas may be composed of degraded pastures, agricultural fields, or tree vegetation in different successional stages (Cavidad-Florez et al., 2020).

In Amazon the above scenario is often related to the species *Bertholletia excelsa Bonpl* (Brazil Nut tree), a widespread species in Amazon which is most common in upland forests ('terra firme" forests) (Mori and Prance, 1990, Shepard and Ramirez, 2011, Levis et al., 2017). Brazil Nut tree is a species with a key role in the region due to their high socioeconomic importance related to its historical relationship with local peoples and their communities, especially in its use for food and the evidence of selection of high productivity genetic material that were planted near occupation sites (Shepard and Ramirez, 2011, Levis et al., 2017; Strand et al., 2018). In addition, Brazil Nut tree is a light-dependent species commonly considered as an indicator of sites with past disturbances (Scoles, 2011). The relatively large size of Brazil Nut trees (over 50 meters in height and 2 meters in diameter) is an important ecological attribute, since these trees may also drive the establishment of adjacent vegetation, mainly by its influence on light availability for other plants (Mori and Prance, 1990, Shepard and Ramirez, 2011, Bertwell et al., 2018).

The process of selective logging in the Amazon leads to the emergence of areas where the dominance of Brazil Nut trees, either natural or artificially-induced, known as Brazil Nut groves ("Castanhais," in Portuguese) (Mori and Prance, 1990, Scoles, 2011; 2016). The maintenance of Brazil Nuts trees individuals in these areas is mainly motivated by the logging legal restriction for this species, and also by their regional importance through the trade and consumption of their valuable seeds (Scoles, 2011, 2016, Strand et al., 2018). Thus, degraded landscapes where Brazil Nut trees occur are common in the region, usually because of recurrent collections of fruit by local workers (Brazil Nut collector – "castanheiro" in Portuguese) (Shepard and Ramirez, 2011, Bertwell et al., 2018, Wadt et al., 2018). These workers make recurrent visits to trees carrying specific instruments used for fruit collection and tools to remove the vegetation near to the Brazil Nut trees or in the path of the worker to the trees, thus implying a local impact on adjacent vegetation and Brazil Nut tree regeneration (Shepard and Ramirez, 2011, Thomas et al., 2015, Wadt et al., 2018).

Although there are no records about the extent of degraded Brazil Nut groves in the Amazon, these areas are likely to have broad occurrence in the region due to the wide distribution and socioeconomic importance of Brazil Nut trees (Mori and Prance, 1990, Shepard and Ramirez, 2011). Many Brazil Nut groves have suffered past disturbances but now are shifting to more advanced sucessional stages through natural regeneration and most time they are part of the Legal Reserve of rural properties (a portion of the forest that must be preserved according to Brazilian environmental laws) (Brancalion et al., 2016, Roitman et al., 2018). Efforts to build knowledge in the vegetation ecological patterns of the Brazil Nut groves are need to build effective restoration and management actions, also considering the role of remaining Brazil Nut trees in the Amazon landscape and the impacts caused by the Brazil Nut trees seed extraction. For example, to better understand the ecology of these communities in Brazil Nut groves, it is important to better understand the relationship between the adjacent vegetation and the Brazil Nut trees that are exploited, considering functional attributes and the influence of anthropic collection activities. Because local communities have a strong economic and cultural relationship with Brazil Nut tree exploitation, the sustainable exploitation of this species may be also included in conservation efforts which link environmental regularization and social benefits in Amazonia, such as in Payment for Ecosystems Services (PES) related to carbon stocks (such as in the Voluntary Carbon market), water resources and natural regulatory services (Ribeiro et al., 2018, Silveira-Junior et al., 2020; Nonini and Fiala, 2021; Bomfim et al., 2022). Such efforts can enhance ecological restoration success without compromising economic activities and regional cultural practices, consequently contributing to the Amazon rainforest conservation and ecosystem services (Strand et al., 2018, Ribeiro et al., 2018; Osaka et al., 2021).

The objective of this article is to evaluate whether the ecological patterns of Brazil Nut groves in the southeastern Amazon (Itaúba region) are affected by morphometric and fruit production factors based on the characteristics of Brazil Nut tree individuals used as focal trees (center of circular plots). We have two hypothesis: i) Brazil Nut trees morphometric characteristics influence the ecological patterns of the tree community in the vegetation adjacent to Brazil Nut trees, due to the shading effects of the Brazil Nut trees), and then, light availability limitations on the surrounding trees."; ii) the fruits production of Brazil Nut trees also influences the ecological patterns of the tree community in vegetation adjacent to Brazil Nut trees due to the impacts from the fruits collection activities, because locations with more productive trees are subjected to more frequent and intensive human actions than the less productive ones. The study also evaluates the carbon storage of Brazil Nut groves components (focal trees and adjacent vegetation) to quantify their potential carbon credit in possible scenarios of commercialization in Payment for Ecosystem Services projects or in the Voluntary Carbon Market. We worked these issues using 15 circular sample units (706.85 m^2 - 1.06 ha) with Brazil Nut tree individuals as a central point (focal trees), in which we sampled the adjacent tree community, as well we monitored the fruits annual production of focal trees production between 2012 and 2017.

MATERIAL AND METHODS

Study area and plot sampling

The study area is a forest fragment of Brazil Nut grove in the Amazon's southern edge, in Itaúba (11º03'42" S; 55º16'35" W), state of Mato Grosso, Brazil (Figure 1), which is a city in which the Brazil Nut production has an importantsocioeconomic role. The regional climate is Koppen Aw (savanna tropical - semi-humid hot) with average monthly temperature of 25.1º and average annual precipitation of 1902 mm. The relief is flat, and the average altitude is 240 m. The forest is classified as Dense Ombrophylous Forest of the Amazon biogeographic domain. The fragment went through selective logging of wood species between 1993 and 1995 but has been partially preserved, despite local impacts associated with the harvest of Brazil Nut tree fruits.

The fragment is part of a research project to monitor biometric and genetic characteristics of Brazil Nut trees (MAPCAST Project – Baldoni et al., 2020), which aims to support management actions, and to expand the knowledge of the numerous social and economic relationships involved in the Brazil Nut extractive activity. Thus, in this area, a group of 102 Brazil Nut trees are monitored for their fruit production in the project context, of which we selected 15 Brazil Nut trees (14.7 %) to be used as the center of circular plots (focal trees) established with a radius of 15 m (706.85 m^2). We have 15 plots established according to the focal trees, totaling a sample area of 1.06 ha (Figure 1). The density of Brazil Nut trees in the fragment is 11 trees/ha.

Data collection

Within each circular plot, we sampled all the trees with diameter at the breast height – DBH (1.3 m) greater than or equal to 10 cm, which had their DBH measured and was identified at the species level. The identification followed APG IV (2016) and the synonym conference followed the Flora do Brazil database (2020). Based on the data collected from vegetation, we obtained six response variables: number of trees, species richness, total carbon stock (ton), carbon stock per tree (ton), community weighted means (CWM) of wood density (g/cm^3) and the floristic dissimilarity matrix between plots using Bray-Curtis as distance measure. The carbon stock was obtained by estimating the above-ground woody biomass (AGWB) through the Chave et al. (2014) pantropical equation for situations in which the height information is not available, using the *BIOMASS* package (Rejou-mechaine et al., 2017). This equation obtains the AGWB by using the DBH information, wood density of the species (obtained from a global database present in the package) and the constant *E* of restrictiveness, which replaces the height information through the expected relationship between this variable and large-scale climatic conditions. To obtain the carbon stock, the AGWB value was multiplied by the constant 0.471, pointed out by Thomas & Martin (2012) as the average carbon concentration in tropical angiosperm tissues. The CWM of wood density was obtained by the *funct.comp* function of the FD package (Laliberté et al., 2014), using the number of individuals as weight measure. The woody density values used as reference for species information are available in the Wood Density Global Database (Zanne et al., 2009).

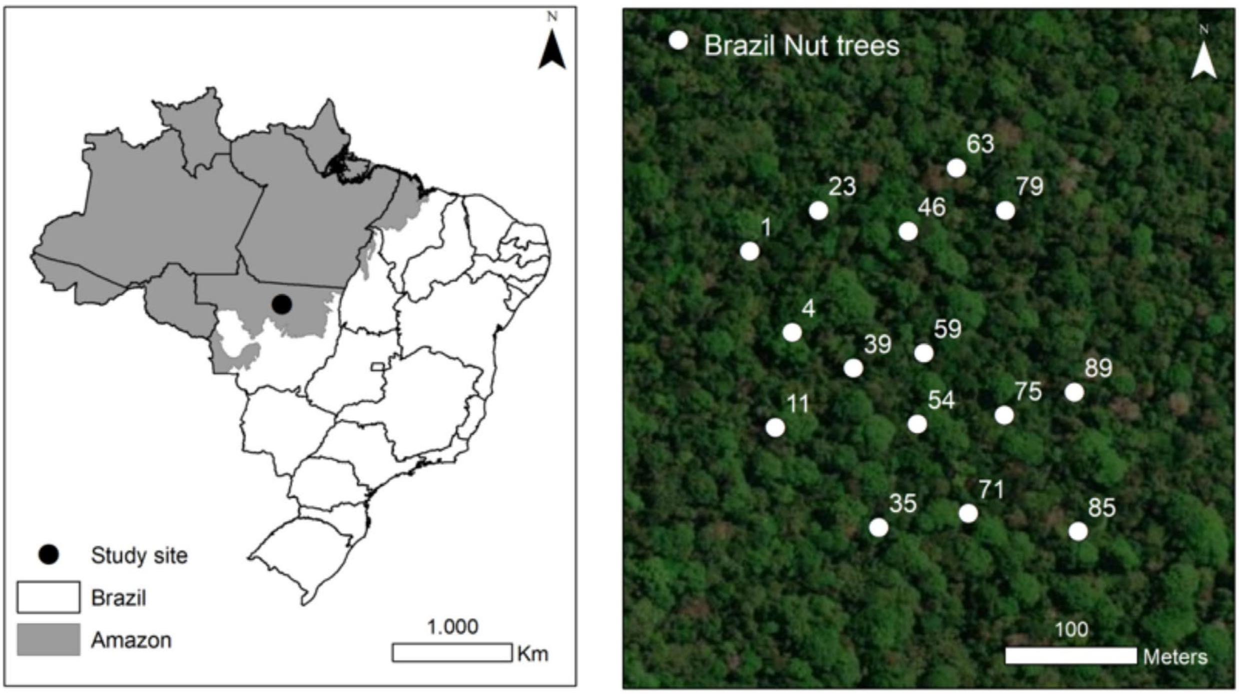

Figure 1: Localization of the study area (left figure) in Amazon and Brazil, and the plots with Brazil Nuts trees in the study area (right figure).

From the focal trees we measured the DBH, tree canopy cover (m^2), and the annual fruit production (kg) between 2012 and 2017. The tree canopy cover was measured by images obtained by Unmanned Aerial Vehicle (UAV) model DJI Phantom 3, with subsequent geoprocessing. The total of fruits in each year was counted and weighed to estimate the annual average (kg) and the coefficient of variation (%) of the annual total production. We chose these variables to obtain information about the pattern and the variability of fruit production from focal trees and thus, be able to characterize individuals. These variables will be used as a proxy for human impacts, since Brazil Nuts trees with higher productivity are more frequently visited by the Nuts collectors. We also obtained the carbon stock of focal trees by the same method applied to trees of the adjacent vegetation.

Data analysis

Focal trees effects on adjacent vegetation

We analyzed the effects of the four explanatory variables from focal trees (carbon stock, canopy cover, average annual fruits production and annual fruits production coefficient of variation) on the six response variables from adjacent vegetation (number of trees, species richness, total carbon stock, carbon stock per tree and CWM of wood density) using generalized linear models (GLM). The GLM are an expansion of the traditional linear models that allow the inclusion of variables from different distribution families, such as poisson and binomial, which may be analyzed in GLM within the context of linear models through a specific link function. By using this method of analysis, we can analyze variables of different distributions within a similar assumptions and interpretation, thus facilitating the analysis of large and heterogeneous data sets. For the response variables number of trees and species richness we used the *Poisson* family distribution while *Gaussian* family distribution was used for the other response variables. We consider the assumptions of overdispersion absence for *Poisson* family and residuals normality and homoscedasticity for *Gaussian* family, that were tested using visual plots and significance tests (like Shapiro-Wilk for normality). For each response variable we obtained four models with only one of the explanatory variables, to be ranked according to the Akaike Information Criterion of second order (AICc). From these four models we selected those with Δ AICc $\leq$ 2. in relation to the best model between them. The selected models were submitted to *multimodel inference* (BURNHAM et al., 2011) to obtain significances and average coefficients, using the *model.avg* function of the "MuMIn" package (Bartón, 2009).

To evaluate the influence of the explanatory variables of focal trees on the variables of species composition of adjacent vegetation in the Brazil Nut grove, we used Permutational Multivariate Analysis of Variance Using Distance Matrices (PERMANOVA) by the *adonis* function of the *vegan* package (Oksanen et al., 2017). We used the floristic distance as the response variable and the focal trees variables as the explanatory variables. We also obtained the phytosociological importance value (IV) of all species of the community to analyze which species are the most successful and their ecological strategies. For the IV obtaining, we used the measure of species total biomass, instead of the species basal area. All analysis were done in the R v. 4.0.3 (R Core Team, 2021)

Carbon credits obtaining for Brazil Nut groves components

The quantification of the potential carbon credits of both Brazil Nut focal trees and adjacent vegetation in Brazil Nut groves was made by converting the carbon stock variable into equivalent CO_2, which is the measure used in the carbon credit futures market or in the Voluntary Carbon Market. For this, we used the correction factor of 3.67, corresponding to the molar mass ratio of a molecule of CO_2 (12+16+16=44) and the mass of an isolated carbon molecule (12). This conversion seeks to estimate the total CO_2 that an amount of carbon can form in the atmosphere. One ton of equivalent CO_2 corresponds to 1 carbon credit available for trading on the carbon futures market or selling in the Voluntary Carbon Market. Then, we explored the relative importance of each component of Brazil Nut groves (Brazil Nut focal trees and adjacent vegetation) to the forest total carbon credits, to discuss potential scenarios of Payment for Ecosystem Services for carbon credits.

RESULTS

Focal trees influence on adjacent vegetation

Overall, we found 526 individuals (491.6 ind/ha) from 93 species (69 identified at the species level, 11 at the genus level, and 13 identified as morpho-species). Above-ground woody biomass of the vegetation adjacent to Brazil Nut trees was of 241.4 tons (225.2 ton/ha), which corresponds to a carbon stock of 113.7 tons C (106.3 ton C/ha) and an equivalent CO_2 stock of 417.3 tons (390.0 ton CO2 eq/ha). The above-ground woody biomass of Brazil Nut trees (focal trees) was of 174.10 tons, corresponding to a carbon stock value of 82.0 tons C and CO_2 stock of 300.9 tons.

We observed significant effects of the Brazil Nut trees variables only on the carbon stock and carbon stock per tree of the adjacent vegetation. These variables were negatively influenced by the variables Brazil Nut trees stock and the Brazil Nut trees canopy cover. This result indicates that forest locations with Brazil Nut trees (focal trees) with larger carbon stock and canopy cover are related to lower carbon stock values and lower carbon stock per tree in the adjacent vegetation (Table 1; Figure 2). For the others response variables (number of trees, species richness, CWM of the wood density and floristic composition) no statistically significant of any explanatory variable were found, that is, only the variables related to the size of trees in adjacent vegetation would be influenced by the Brazil Nut trees. Therefore, the adjacent vegetation in the Brazil Nut groves studied at different points is composed by the same species group with similar functional traits, species richness, and tree density (Table 1). The variables associated with fruit production of Brazil Nut trees have no significant influence on any of the adjacent vegetation variables. However, it is important to consider that reproductive attributes have a particular ecological complexity that makes it difficult to assess its ecological patterns and requires great efforts in including other information related to environment and interactions (Table 1). The group of species of most significant ecological importance (higher IV values) was composed of species of different ecological strategies, whereby some of them have their importance associated with a high number of trees, such as *Protium sagotianum* Marchand. In contrast, others species have their importance related to larger trees, such as *Goupia glabra* Aubl., and *Bertholletia excelsa* Bonpl, which is also important in the adjacent vegetation (Table 2).

Table 1: Results obtained by the analysis of effects of the Brazil Nut trees (focal trees) variables (columns) on the adjacent vegetation variables (rows), obtained through *multimodel-inference* (first 4 rows) and by Permutational multivariate analysis of variance (PERMANOVA) for the Bray- Curtis floristic similarity (fifth row), for the 15 circular plots evaluated in Brazil Nut groves in Amazon. Cells filled with "ns" represent the non-significant effect of the explanatory variable on the response variable considering 0.05 as the significance level (p > 0.05), while * means p ≤ 0.05, ** indicate p ≤ 0.01, *** indicate p ≤ 0.001 and **** indicate p ≤ 0.0001. Besides the p-value, variables with significative effects also present the estimate ("est") obtained for the relationship between variables. Note: AA FP: Annual Average Fruits Production; CV FP: coefficient of variation of fruits production; CWM: community weighted means.

Response variables	Brazil Nut trees variables - Explanatory variables			
	Nut Carbon Stock	Nut Canopy cover	AM FP	CV FP
Number of trees	ns	ns	ns	ns
Species richness	ns	ns	ns	ns
Carbon stock	p = 0.003** / est = -0.33	p = 0.0004*** / est = -0.34	ns	ns
Carbon stock per tree	p = 0.008** / est = -0.06	p = 0.009** / est = -0.06	ns	ns
CWM wood density	ns	ns	ns	ns
Floristic similarity	ns	ns	ns	ns

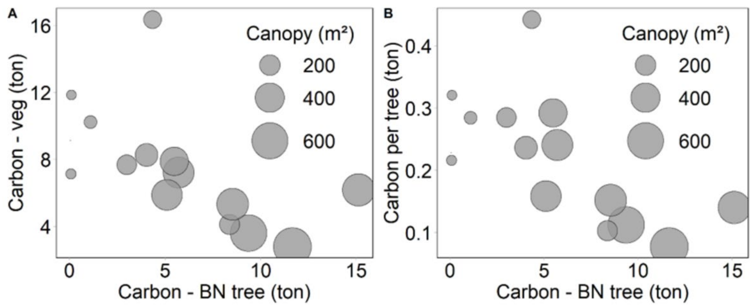

Figure 2: Visual relationship between the response variable adjacent vegetation carbon stock (a) and carbon stock per tree (b) with the explanatory variables Brazil Nut trees carbon stock and Brazil Nuts trees canopy cover (circles) for the 15 plots evaluated in Brazil Nut groves in the Amazon.

Table 2: 10 Species of greater phytosociological importance value (IV) for the adjacent vegetation in 15 plots of Brazil Nut groves evaluated in Amazon. For each species is presented their values of relative density (RD), relative dominance (RDo), relative frequency in plots (RF), cover value (CV) and phytosociological importance value (IV)

Species	RD	RDo	RF	CV	IV
Pseudolmedia laevis (Ruiz & Pav.) J.F.Macbr.	14.64	12.84	5.70	13.74	11.18
Tovomita umbellata Benth.	9.32	7.77	5.32	8.54	9.03
Protium sagotianum Marchand	17.30	4.45	5.70	10.87	8.38
Matayba arborescens (Aubl.) Radlk	4.56	1.18	4.56	2.87	5.91
Bertholletia excelsa Bonpl.	0.76	11.30	1.52	6.03	5.61
Pouteria bilocularis (H.K.A.Winkl.) Baehni	3.80	2.68	3.80	3.24	5.50
Goupia glabra Aubl.	0.95	10.75	1.52	5.85	5.42
Metrodorea flavida K.Krause	4.75	2.05	3.04	3.40	4.36
Mezilaurus itauba (Meisn.) Taub. ex Mez	0.95	4.57	1.90	2.76	3.82
Erisma uncinatum Warm.	0.95	2.57	1.90	1.76	3.16

Carbon credits of the Brazil Nut groves components

The amount of carbon credits in the Brazil Nut trees (focal trees) vegetation adjacent was higher where the Brazil Nut tree's carbon credits amount was lower, in agreement with the result shown previously (Table 1; Figure 2). The amount of carbon credits in the adjacent vegetation ranges between 145.15 and 849.68 credits per ha, while the amount stored in the woody tissues of the Brazil Nut tree (focal-tree) ranged between 2.52 and 785.02 carbon credits per ha (Figure 3 – A). The representativity of each component of the Brazil Nut grove change markedly between plots ranging from 19.35 to 99.47 % for adjacent vegetation and from 0.52 to 80.65 % for Brazil Nut trees (Figure 3 – B). Considering the interaction of carbon credits components representativity with fruit production, we observed a heterogeneous pattern of the trend, where there are larger BN trees that produce more fruits, and BN trees with intermediate sizes with similar productions to the largest BN trees (Figure 3 B). Thus, for the studied area, there is no clear relationship between the carbon credit components and fruit production, while the carbon stock relationship between BN trees and adjacent vegetation showed to be the most important association to produce the observed patterns.

DISCUSSION

Our results confirmed our first hypothesis that morphometric variables of Brazil Nut trees have effects on the ecological patterns of the adjacent vegetation to Brazil Nut trees in Brazil Nut groves, but rejected the second, because we have not found significant effects of fruit production related variables. Therefore, our results points that Brazil Nut trees influence the adjacent vegetation in Brazil Nut groves through the ecological effects of their size, considering the effects of Brazil Nut trees carbon stock and canopy cover on the vegetation variables of total carbon stock and carbon stock per tree. Thus, along the forest locations in Brazil Nut groves, there are a similar group of species with similar functional patterns, species richness, and tree density. We also found that Brazil Nut groves possess an opportunity to the exploration of carbon credits, but there are variations in the relative importance of each component of the Brazil Nut groves (focal trees and adjacent vegetation) related to differences in their sizes, as well as the average annual fruits production of Brazil Nut trees.

The negative effects of Brazil Nut trees' size variables on the adjacent vegetation size attributes are probably related to processes of interaction and competition for light between trees (Aschehoug et al., 2016), since the presence of large individuals of Brazil Nut tree may limit the access of adjacent lower size trees to this resource. Therefore, in places where Brazil Nut trees have larger sizes (greater canopy area and carbon stock), the trees in the adjacent vegetation may be subject to lower light availability that reduce individual growth (carbon stock per tree) and consequently decrease total carbon stock in adjacent vegetation. This effect is further highlighted by the absence of a significant effects of Brazil Nut trees variables on the tree density that reinforces competition effects only on the trees individual size. Thus, forest locations with Brazil Nut trees of different sizes have a similar number of trees but these trees may exhibit varying levels of success in carbon sequestration at the individual tree level in adjacent vegetation. The light availability is considered one of the main limiting factors for plant success in the various vertical strata, in forests where there is no marked water deficit or soils with extremely restrictive physicochemical characteristics such as in Amazon (van Breugel et al., 2012, Laurans et al., 2014, Kraft et al., 2015, Aschehoug et al., 2016, Cadotte and Tucker, 2017). This factor is even considered as a driver of biological diversity in tropical forests and is one of the main factors to be managed for effective forest recovery actions (van Breugel et al., 2012, Santos et al., 2020).

The absence of significant effect of these variables related to the size of the Brazil Nut trees (focal trees) on the species richness, floristic composition and functional composition of the adjacent vegetation may be associated with a secondary effect of competition, and/or a preponderance of other factors in driving these patterns in the forest stratum considered in this study (Cadotte and Tuker, 2017). In the evaluated stratum (DBH ≥ 10 cm), the effects of light restriction on the adjacent vegetation by the competition with Brazil Nut trees may not be strong enough to determine how many and which species will occupy it, determining only the size of the trees present in the adjacent points. Since there are no dispersion limitations on the evaluated spatial scale (the focal trees are no more than 500 m

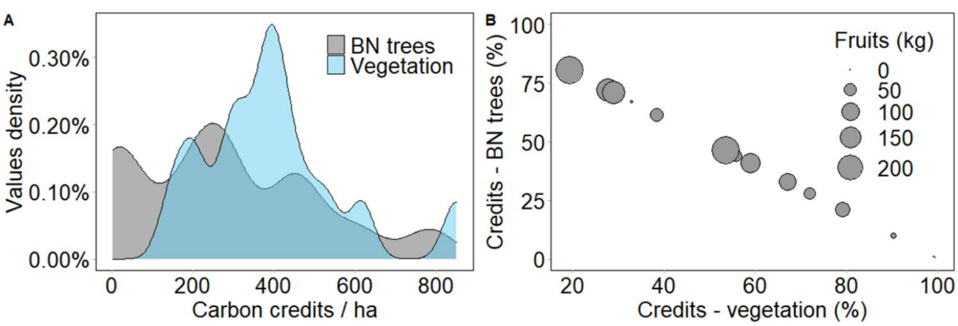

Figure 3: Range of carbon credits values observed in plots for each component of the Brazil Nut grove (a) and the relation between the representativity (%) of the carbon credits of each component to the Brazil Nut grove as a whole. In the second figure, the point size is scaled according to the annual average fruit production observed between 2012 and 2017.

from each other), all species can reach all forest points sampled, that is, variations in species richness and composition along the forest may occur only through ecological filters that act after colonization (Kraft et al., 2015, Cadotte and Tucker 2017). Thus, species composition, species richness and functional composition in the evaluated stratum may be determined before individuals reach the minimum size considered, since the competition for light with the focal trees has a weak effect to drive these variables in the stratum (van Breugel et al., 2012, Laurans et al., 2014, Norden et al., 2015, Aschehoug et al., 2016).

The results indicate an absence or small effect of Brazil Nut trees fruits production variables on adjacent vegetation characteristics, indicating that activities related to the fruits collection have not important impacts in the adjacent vegetation and their ecological patterns, at least for the evaluated forest strata. As previously discussed, the potential impacts of these activities may have their effects mainly in the strata with trees smaller than the one evaluated, in which the Brazil Nut collector meets directly (Shpeard and Ramirez, 2011, van Breugel et al., 2012, Laurans et al., 2014, Bertwell et al., 2018). However, such effects are complex to measure because these impacts still interact with environmental shifts and biological interactions along the succession(Chazdon, 2014, Norden et al., 2015, Aschehoug et al., 2016, Cadotte and Tucker, 2017). Another relevant result is the identification of potential species for restoration efforts within Brazil Nut groves, as noted in the list of dominant species. These species present differentiated strategies (i.e., trade-off between the number of individuals and biomass), which should be considered when planning possible implantation actions (Chazdon, 2014). Brazil Nut tree itself is present in the top 10, with low density and high biomass in the adjacent vegetation, which points out to consider the potential future fruits exploration as another reason to include this species in restoration activities in the region (Shepard and Ramirez, 2011; Strand et al., 2018).

Our results also showed that the Brazil nut trees' carbon credits have the potential to be profitable to the rural owners who have forest areas in which this species are present. On 15 Sep 2022, for example, one carbon credit had a value €$ of 72.11 on the London Stock Exchange (Investing 2022). Considering the values obtained from the samples, the carbon credit values observed in this study could range from to €$ 10,466.77 to €$ 61,270.42 for adjacent vegetation and from €$ 181.71 to €$ 56,607.79 for the Brazil Nut trees used as focal trees, while the minimum wage practiced in Brazil in 2022 was R$ 1212 that is equivalent to €$ 231.5 (1 €$ = R$ 5.23 in 15 Sep 2022). Considering the expected development of an effective global carbon market, these values can complement the income obtained from the fruits collection or other non-timber forest products (such as rubber). This income may also be a stable incoming value that can fill production gaps, climatically unfavorable periods, or situations in which Brazil Nut trees do not yet present reproductive age (Mori and Prance, 1990, Ribeiro et al., 2018, Warren-Thomas et al., 2018). In the latter context, the carbon credits from the surrounding vegetation may be especially interesting, since in this situation the carbon from adjacent vegetation is higher, and the possible gains are even higher. However, it is also important to consider variations in the Brazil Nut trees individuals' density since there are records of a range of densities (lower to greater than those found here) due to the local anthropic history (Mori and Prance, 1990, Wadt et al., 2005, Scoles and Gribel 2011, Neves et al., 2016).

Strategies related to carbon credits are inserted in the so-called "Payments for Environmental Services," in which people receive some economic return for performing some activity that guarantees the provision of essential environmental services (Zhang, 2016; Silveira-Júnior et al., 2020; Osaka et al., 2021). In the carbon credit market, companies that emit more carbon into the atmosphere than they should have (by established standards) will have the opportunity to pay for the keeping of the same amount conserved in forest or in other nature-based solutions (Grieg-Gran et al., 2005, Perdan and Azapagic, 2011; Fearnside, 2018; Nonini and Fiala, 2021; Bomfim et al., 2022). Thus, people or organizations with carbon credits available for sale put them on the carbon sale market, where they can be traded (Perdan and Azapagic, 2011; Nonini and Fiala, 2021). Initiatives like this can contribute to the conservation and restoration of tropical forests, as it encourages the conservation of the remaining vegetation, while stimulating the non-impediment to the natural regeneration of degraded areas in rural properties (Fearnside, 2008, Moutinho et al., 2011, Zhang, 2016, Brancalion et al., 2016, Ribeiro et al., 2018, Warren-Thomas et al., 2018; Nonini and Fiala, 2021).

In the context of Amazon region and degraded Brazil Nut groves, payment for environmental services can also contribute to the environmental regularization of rural properties, considering that these areas correspond to a large part of the environmental liability of legal reserves, which must occupy at least 80% of the land total area according to the Brazilian Forest Code (Moutinho et al., 2011, Brasil, 2012, Fearnside, 2016). Furthermore, since legal reserves are open to sustainable management, these payments for environmental services related to carbon credits may also be joined to the commercial exploration of Brazil nut seeds (Strand et al., 2018; Osaka et al., 2021). Moreover, these areas may increase their associated value considering the presence of the Brazil Nut tree individuals and other important fauna elements, which can increase the value of the forest, according to the principle of additionality and co-benefits. Thus, rural property environmental regularization can be achieved with financial incentives from carbon credits and the Brazil Nut seeds exploration, in addition to incentive the forest conservation in the Amazon region and also of the cultural heritage related to local activities with the Brazil Nut trees (Grieg-Gran et al., 2005, Shepard and Ramirez, 2011; Osaka et al., 2021).

The survey of the potential economic benefits that can be derived from the sale of carbon credits highlights the need for further attention. to the voluntary carbon market in Brazil. There is not muchregulation on legislation, guidelines, quantification manuals, or reference documents that discuss the role of native forests, which ends up hindering the sector development and consequently avoiding the benefits obtaining (Moutinho et al., 2011, Souza et al., 2013, Fearnside, 1999, 2008, 2018; Osaka et al., 2021). There are still gaps in how to incorporate dynamic vegetation processes that generate variation in the carbon stock. Examples are mortality and recruitment of individuals, floristic and functional composition variations, and other processes related to the ecological trajectory that also produce variations in the carbon stock (Fearnside, 2008, Aragão et al., 2014, Chazdon, 2014, Norden et al., 2015; Nonini and Fiala, 2021). We highlight that the values shown are not final values, since there is a great economic complexity, such as the inclusion of taxes, opportunity costs and variations in supply. The inclusion of financial returns in long term planning is likely to modify the values obtained, in addition to determining whether the values will be received annually, within what time frames, and under what conditions. The values obtained in our results demonstrate the potential for obtaining financial returns with their incorporation in payments for environmental services projects. It is also important to point out that our study has a limited sample for the Amazon as a whole, limiting itself to pointing out scientific remarks for future comprehensive studies to be carried out in the Brazil Nut groves. These regions, scattered throughout the Amazon, are crucial for conservation efforts and warrant further study to understand their ecological patterns and significance.

CONCLUSION

Our research revealed that the ecological patterns of Brazil nut groves in the Amazon are shaped by the size of the Brazil Nut trees, which not only determines the size of the trees themselves, but also influences the structure of the adjacent vegetation. The economic evaluation demonstrates the potential financial return with the sale of carbon credits from the Brazil nut trees and the adjacent vegetation. These strategies can assist in obtaining social and economic gains for rural landowners and local communities, while also contributing to the Amazon conservation.

AUTHORSHIP CONTRIBUTION

Project idea: CRS, ABB, HT, VAM, RMS, ML, JPS

Database: CRS, ABB, HT, VAM, RMS, ML, JPS

Processing: CRS, ABB, HT, VAM, RMS, ML, JPS

Analysis: CRS, ABB, HT, VAM, RMS, ML, JPS

Writing: CRS, ABB, HT, VAM, RMS, ML, JPS

Review: CRS, ABB, HT, VAM, RMS, ML, JPS

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